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SOLIDIFICATION/STABILIZATION OF SLUDGE AND ASH FROM WASTEWATER TREATMENT PLANTS

by

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16. ABSTRACT

Tests were performed to determine the physical properties and chemical leaching characteristics of the residuals and the stabilized/solidified products from two publicly-owned wastewater treatment works (POTW). The two POTW waste products included in this study were an anaerobic digester sludge from an Imhoff digester and an ash from a rotating hearth incinerator used to destroy primary settler and digester sludges.

Three different solidification/stabilization systems were used. One of the systems was based on the addition of cement and soluble silicates in various proportions and formed soil-like solids that were soft and easily broken. A second system used lime and flyash to form a pozzolanic material that produced a hard, concrete-like solid. The third system was based on the formation of gypsum in the waste after acidification; these products remained wet and did not harden.

None of the treated products were very durable, as none survived the full sequence of 12 cycles and the wet-dry or freeze-thaw testing. The pozzolanic, flyash-lime product reduced the loss of constituents to the leaching medium to the greatest extent. It also produced by far the smallest increase in the weight of the waste to be disposed for any of the processes--170% of the dry sludge solids. These facts coupled with the low cost of the solidification agents make this process the most cost-effective of those tested in this study.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report presents results from the laboratory testing of solidified or chemically stabilized residues from wastewater treatment plants. The treated products in some cases represent a superior material for landfilling, with better containment properties and more desirable handling characteristics than dewatered sludge cake. Research of this type can improve disposal methods for the potentially toxic byproducts of water treatment and result in minimum degradation of the land disposal area.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The physical properties and chemical leaching characteristics of two different, publicly-owned, wastewater treatment works residual materials and their stabilized/solidified products are reported. The two POTW waste products included in this study were an anaerobic digester sludge from an Imhoff digester and an ash from a rotating hearth incinerator used to destroy primary settler and digester sludges.

Three different solidification/stabilization systems were used. One of the systems which was based upon the addition of cement and soluble silicates in various proportions formed soillike solids which were soft and easily broken. A second system used lime and flyash to form a pozzolanic material which produced a hard, concretelike solid. The third system was based upon the formation of gypsum in the waste after acidification; these products remained wet and did not harden. The Imhoff sludge (anaerobic digester waste) was treated with formulations of the cement-soluble silicate process; the incinerator ash was treated by all three processes.

None of the treated products were very durable as none survived the full sequence of 12-cycles of the wet-dry or freeze-thaw testing. The concrete-like, lime-flyash solid had the highest durability, surviving 11 freeze-thaw and five wet-dry cycles. The soil-like products survived two or less cycles of both durability tests. The gypsum-based product remained moist and putty-like and could not be tested for durability.

The pozzolonic, flyash-lime product reduced the loss of constituents to the leaching medium to the greatest extent. It also produced by far the smallest increase in the weight of the waste to be disposed for any of the processes--170% of the dry sludge solids. These facts coupled with the low cost of the ingredients make this process the most cost effective of those tested in this study.

Both wastes types were treated by the cement-silicate based process with nearly equal effectiveness in retarding leaching losses. Their soil-like texture also improved their ease of handling. However, the process as used in this study, greatly increased the amount of the waste which must be disposed--from 500 to 1500% of the original dry sludge solids (by weight). This was due largely to the amount of water which made up 65 to 70% of the weight of the final product. Of the two formulations of this process used on the Imhoff sludge, the one with the higher additive-to-sludge ratio was more effective in holding constituents from leaching, but probably not improved enough to warrant the extra bulk and cost of additive for routine sewage sludge or ash stabilization.

The static leaching test developed for this study proved to be an effective way to evaluate and compare the leaching potential of both solid and semi-solid test specimens. The incorporation of a cellulose extraction thimble prevented particulates from being removed during the daily leachate renewal. However, the 90-day leaching period employed was longer than needed to assess leaching losses; two weeks leaching time with daily leachant replacement provided sufficient data for reliable leaching potential evaluation for the products used in this experiment.

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CONTENTS

	Page
Foreword	iii
Abstract	iv
Figures	viii
Tables	ix
Acknowledgments	xii
1. Introduction	1
2. Conclusions	4
3. Recommendations	6
4. Methods and Materials	7
Sources, Selection and Description of POTW Wastes	7
Selection of Sludge Processors	9
Leaching Test Design	11
Chemical Analyses	12
Physical Testing	17
5. Results	20
General Character of Treated and Untreated Test Specimens	20
Results of Physical Testing	20
Results of Leach Testing	27
Treated Incinerator Ash Constituent Leaching Results	51
6. Discussion	56
References	59
Appendices	
A. Data Set for Metals, Anions, and Total Organic Carbon	61
B. Data Set for pH and Conductivity	71

FIGURES

Number		Page
1	Design of leaching apparatus	13
2	Leaching apparatus in use on samples of XA, XB, and X treated products	14
3	Photo of Imhoff digestor sludge	21
4	Photo of sludge incinerator ash	21
5	Specimen of process X treated incinerator ash after failure	25
6	Specimen of process X treated incinerator ash after failure	25
7	Specimens in wet-dry test after one cycle	26
8	Specimens in wet-dry test after two cycles	26
9	Concentration of sulfate leached from untreated sludges	29
10	Concentration of manganese in leachate from treated and untreated incinerator ash	30
11	Concentration of zinc in leachate from untreated sludges	31
12	Mean weekly pH values of Imhoff sludge leachate	33
13	Mean weekly pH values of leachate from incinerator ash sludges	34
14	Mean weekly conductivity of leachate from Imhoff sludges	35
15	Mean weekly conductivity of leachate from incinerator ash sludges	36
16	Daily average conductivity values for selected sludges for days 6 through 24	37

TABLES

Number		Page
1	List of POTW Wastes Studied, Designation in this Study, and Solidification/Stabilization Process Employed	8
2	Chemical Composition of Treated and Untreated Imhoff Sludges	8
3	Chemical Composition of Treated and Untreated Incinerator Ash Sludges	9
4	Formulation and Column Loading for Wastewater Treatment Plant Sludges	10
5	Schedule for Sampling for Chemical Analyses	15
6	Methods of Preservation of Leachate Samples	15
7	Parameters Analyzed and Limits of Detection	16
8	Amount (mg) of Each Constituent in the Test Samples of Imhoff Sludge	17
9	Amount (mg) of Each Constituent in the Test Sample of Incinerator Ash	18
10	Summary of Physical Properties of Imhoff Sludges	22
11	Summary of Physical Properties of Incinerator Ash	23
12	Average Weekly pH and Conductivity Values for Blank Vessel Leaching Test	28
13	Composition of Leachate from Untreated Imhoff Sludge Leaching Test	38
14	Average Weekly pH of Leachate from Imhoff Sludges	39
15	Average Weekly Conductivity of Leachate from Imhoff Sludges	40

Number		Page
16	Composition of Leachate from Untreated Incinerator Ash Sludge Leachate Test	41
17	Average Weekly pH of Leachate from Incinerator Ash Sludges	42
18	Average Weekly Conductivity of Leachate from Incinerator Ash Sludges	43
19	Duncan's Range Test of Significant Difference in the Mean Total Mass of Constituents Leached from Imhoff Sludges	44
20	Duncan's Test of Significant Differences in the Mean Total Mass of Constituents Leached from Incinerator Ash	45
21	Duncan's Test of Significant Difference in the Mean Total Fraction of Constituents Leached from Imhoff Sludges	46
22	Duncan's Test of Significant Differences in the Mean Total Fraction of Constituents Leached from Incinerator Ash Sludges	47
23	Total Mass of Constituents Leached from Imhoff Sludges	48
24	Total Constituent Fraction Leached from Imhoff Sludges	49
25	Total Mass Leached from Incinerator Ash	52
26	Total Fraction Leached from Incinerator Ash	53
A-1	Leaching Loss of Metals, Anions, and Total Organic Carbon from Blank Leach Vessels	62
A-2	Leaching Loss of Metals, Anions, and Total Organic Carbon from Untreated Imhoff Sludge	63
A-3	Leaching Loss of Metals, Anions, and Total Organic Carbon from Imhoff Sludge Treated by Process XA	64
A-4	Leaching Loss of Metals, Anions, and Total Organic Carbon from Imhoff Sludge Treated by Process XB	65
A-5	Leaching Loss of Metals, Anions, and Total Organic Carbon from Untreated Incinerator Ash	66
A-6	Leaching Loss of Metals, Anions, and Total Organic Carbon from Incinerator Ash Treated by Process X	67
A-7	Leaching Loss of Metals, Anions, and Total Organic Carbon from Incinerator Ash Treated by Process Y	68

Number		Page
A-8	Leaching Loss of Metals, Anions, and Total Organic Carbon from Incinerator Ash Treated by Process Z	69
A-9	Reservoir Blank Values of Metals, Anions, and Total Organic Carbon	70
B-1	Daily pH values of Leachate Samples from Vessels Containing Imhoff Sludges (Treated and Untreated)	72
B-2	Daily Conductivity Values of Leachate Samples from Vessels Containing Imhoff Sludges (Treated and Untreated)	74
B-3	Daily pH Values of Leachate Samples from Vessels Containing Incinerator Ash Sludges (Treated and Untreated)	76
B-4	Daily Conductivity Values of Leachate Samples from Vessels Containing Incinerator Ash Sludges (Treated and Untreated)	78

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SECTION 1

INTRODUCTION

The effects of groundwater and surface water contamination from publicly-owned sewage treatment works (POTW) wastes are not completely known. The potential problems inherent in treatment, disposal, and/or utilization of these sludges fall into the general categories of (1) public health issues, (2) technological factors, and (3) social/economic/institutional factors (U. S. Environmental Protection Agency, 1978). To implement an overall policy, resolutions are needed for these problems that presently inhibit the disposal or use of POTW residues, and new strategies for managing the residues must be investigated.

The purpose of this study was to assess the effectiveness of commercially available chemical fixation treatments in improving the handling characteristics and in restricting the release of potentially toxic constituents to contacting waters. Two different POTW wastes were treated using commercially available stabilization technology offered by three companies. The effect of solidification was evaluated by changes in selected physical and engineering properties of the waste. The treated and untreated wastes were exposed to leaching conditions in specially designed leaching vessels for 90 days in a controlled environment. The resulting leachates were analyzed chemically for selected metals and anions. The chemical leaching data were used to assess the effectiveness of the stabilization processes in limiting the loss of POTW waste constituents to contacting waters.

BACKGROUND

Current legislation in the form of the Safe Drinking Water Act, the Clean Water Act, and the Resource Conservation and Recovery Act limits the levels of organic and inorganic compounds that can be introduced into the groundwater or surface water as leachate from treated and untreated sludges or other wastes (U. S. EPA, 1980a). In handling sludge or ash, wastewater treatment plants are faced with essentially two options: (1) Indefinite storage (e.g., lagooning), or (2) disposal (and/or utilization). Disposal may require additional treatment (conversion) of the dewatered sludge or ash (e.g., incineration, pyrolysis, stabilization, or composting), or it may be possible using direct land disposal through landspreading and landfilling.

The potential for unacceptable levels of groundwater contamination has been documented in several cases where POTW wastes (especially sludges) were disposed of in lagoons, landfills, and landfarms. Cadmium, copper, and zinc have been observed to penetrate the soil to a depth of 3 m beneath one wastewater sludge lagoon (Page and Pratt, 1975). In another study, Wilson (1975)

concluded that problem levels of iron, manganese, nitrate, cadmium, lead, and silver could develop below a sludge landfill or impoundment site. Eighty-five cases of groundwater and/or surface water contamination associated with leaky impoundments in 29 states were cited by Geraghty and Miller Inc. (1978). Between 1969 and 1976, 130 to 470 dry metric tons of sludge per hectare was plowed into a POTW disposal area near Denver, Colorado. Wells in the area considered to be affected by the sludge disposal operation showed elevated levels of nitrate, chloride, ammonia, and magnesium. Sulfate and manganese concentrations exceeded the National Interim Primary Drinking Water Standards (Robson, 1977). Miller et al. (1974) have reported the leaking of millions of gallons per year of potentially hazardous substances from lagoons, pits, and basins.

The above studies point to the need for improved POTW sludge disposal technology. Several responses to this problem are being actively pursued under private and government auspices. Some familiar examples are the use of stable, abandoned mines for the disposal of hazardous or radioactive wastes (McClain, Bradshaw and Emson, 1967) and deep ocean dumping for the less noxious wastes such as the POTW sludge of this study (Lunt et al., 1977; U. S. Environmental Protection Agency, 1976a). Special land treatment or land cultivation techniques are also under active investigation for sewage sludges and selected industrial wastes of high organic content (Phung, Barker, Ross, and Barnes, 1978). Systems for isolating landfills with impervious liners or landfilling noxious materials in sealed containers are also being developed (Fields and Lindsey, 1975).

STUDY OBJECTIVES AND DESCRIPTION

This study is concerned with another alternative to POTW sludge disposal--that of chemically stabilizing (fixing) or structurally isolating the residual material in a solid, crystalline, or polymeric matrix so that the resulting treated product can be safely handled, transported, and disposed of using established methods of landfilling or burial.

Chemical fixation and solidification/stabilization are general terms used to designate processes that can be used to immobilize, isolate, or otherwise contain waste materials, especially semisolids or sludges (Malone and Jones, 1979). Solidification suggests the production of a solid, monolithic mass with sufficient structural integrity to be handled, transported, and/or disposed of in some conveniently sized pieces without requiring any secondary containers. Stabilization implies the immobilization of toxic substances by reacting them chemically to form insoluble compounds or to entrap the toxic element or compound in a watertight, inert polymer or stable crystal lattice. Much of the emphasis in stabilization has been placed on preventing the waste from coming into contact with leaching waters, or on creating pH and/or oxidation-reduction conditions that minimize the solubility of the toxic constituents. Many fixation systems combine these two ideas by producing an impermeable mass that isolates the waste (or reduces its leachable surface area) and also maintains the pH and oxidation-reduction potential in the region of minimum solubility of the toxic components (Malone and Francingues, 1981).

At the beginning of this investigation, 36 vendors of waste fixation technology were identified, and 17 vendors were selected as having potentially successful treatment processes and were approached concerning the application of their process to the two wastes included in this study. Five companies expressed interest and made preliminary treatment tests on the sludges. Of the three who ultimately agreed to take part, only one treated both wastes.

The solidification/stabilization processes involved in this study include those marketed by companies that volunteered to treat POTW wastes, but the selection does represent a cross-section of those processes available commercially or being developed at this time. A pozzolan-based process and a gypsum-based system (both of which only treated incinerator ash) and a cement-soluble silicate process that produced two treatment mixes for organic sludge and one for incinerator ash are evaluated in this study.

The wastes selected for this study represent two types of wastewater treatment residues: (1) An organic sludge produced by an Imhoff anaerobic digestor, and (2) an ash from a sewage sludge incinerator. The Imhoff tank sludge is an air-dried, felt-like material containing recognizable debris (e.g., hair, plastic scraps, rubber bands, etc.). This sludge has been sold and used as a soil additive; it has little odor and is greenish to gray-black in color. The incinerator ash is a dry, light powder that varies from brown to orange. The sample used in this study was collected directly beneath the incinerator gratings. The ash has a slight musky, soil-like odor and contains a few large (5- to 10-cm diameter) slaglike agglomerations. Both wastes contain variable amounts of water and solids (inorganic and organic). The Imhoff sludge has a higher water content than the incinerator ash. In addition, the organic carbon content of the Imhoff sludge is considerably higher than the incinerator ash. Volatile constituents such as sulfate and cadmium were present in lower concentrations in the ash compared with the Imhoff sludge. On a dry weight basis, the metals chromium, selenium, copper, iron, and zinc were also found in significantly lower amounts in the ash than in the Imhoff sludge. Only manganese was present in higher concentrations in the incinerator ash.

The ability of the treated and untreated sludges to resist loss of their constituents to contacting waters can be determined by short-term laboratory leaching tests (Lowenbach, 1978). Many leaching procedures have been proposed and evaluated (Ham and others, 1979). The leaching procedures employed in this study represent a combination of those described previously, and they incorporate several aspects unique to this study. The sample specimens used are of a size and shape typical of those used for the universal leaching procedure (ULP), a proposed standard test for solidified wastes (Malone, Jones, and Larson, 1980). The specimens to be leached were placed in a cellulose thimble to prevent particulates from being lost to the leaching medium. The thimble also allowed the identical leach testing of untreated and treated sludge specimens.

SECTION 2

CONCLUSIONS

Laboratory studies of the physical properties and chemical leaching characteristics of five commercially available stabilization/solidification techniques have been conducted. Two of these processes have been used in the treatment of the waste produced by an anaerobic Imhoff digestor tank, and three were used in treatment of the ash from a rotating-hearth sludge incinerator. The two processes used in treatment of the Imhoff sludge were similar cement/soluble silicate systems (except for the proportion of reagents to sludge solids) and were similar to one of the treatments used for the incinerator ash. A pozzolan cement and a gypsum-based process were also used on the ash waste. Data from these investigations can be used to evaluate potential pollution problems inherent in the treatment, disposal, and/or use of the residual materials produced by publicly-owned wastewater treatment plants.

Standard physical and engineering tests performed on the treated wastes indicated that the treatment processes did not always change the physical properties in a way that would insure production of a solid. Only one of the treatment processes produced a material that resembled low-strength concrete in character. The strongest product was obtained by applying a pozzolan-lime-flyash process to ash. Other treatments of the incinerator ash produced a soil-like product and a wet plaster-like product that did not harden. Both processes that treated the Imhoff sludge produced soil-like products. The durability of the final products was low. No product survived the full 12 cycles of wet-dry or freeze-thaw testing. The lime-flyash product was the most durable, surviving 11 cycles of freeze-thaw and 5 cycles of wet-dry testing. The soil-like products survived only two cycles of either test. The wet product from the gypsum process was not tested.

The leaching procedure used in this testing program was designed to control many factors that affect leaching rates. The leaching of the constituents is proportional to the concentration of the constituent in the waste, the solubility of the constituent, and the time of leaching. Biological factors, though not controlled, were assumed to play no role because of the relatively short time (90 days) involved in the leaching test.

The loss of constituents in the leachate from the test samples followed one of three distinct patterns. Highly soluble constituents (e.g., sulfate and chloride) were leached in high concentrations initially and quickly reached a very low level at or below the analytical detection level for the remainder of the testing period. Less soluble constituents (e.g., lead and chromium) were found at relatively constant levels in the leachate. In several cases (cadmium, copper, manganese, and zinc), the initial leachate

samples contained elevated levels of the constituent before a constant concentration was obtained. One constituent, arsenic, was at or below detection levels initially but increased in concentration in later samples as the pH of the leaching liquid changed during the course of the testing.

The leaching tests indicated that several of the processes significantly slowed the leaching of selected constituents. Overall, both processes used in treatment of the Imhoff digestor sludge significantly slowed the leaching of soluble constituents. The process with the higher reagent-to-sludge solids ratio was more effective than the sludge-rich mixture. In treatment of the incinerator ash, the gypsum-based process was not effective in stabilizing the sludge or in limiting the loss to leaching from the test samples. Of the other two treatments tested with the ash, both were able to slow the leaching loss from the samples. The lime-flyash process product was the most effective treatment.

One processor treated both types of waste and used a cement/soluble-silicate system. The results obtained by this processor indicated no difference in the relative effectiveness of treating the two waste types. The appearance, physical properties, and leachability of the two wastes fixed by the same process were quite similar.

Only the lime-flyash process produced a stabilized product with more than 20% dry sludge solids (by weight); the lime-flyash process had about 60% dry sludge solids in its final product (or an increase in volume of only 1.5 times). The other processes increased the amount of waste to be disposed of by from about 4 times to as high as 10 times, largely due to the addition of water in high proportions (65 to 70% of the final weight). In evaluating the use of solidification/stabilization on a commercial basis, the 4-to-1 increase in mass to be disposed must be considered along with the improved pollutant containment.

SECTION 3

RECOMMENDATIONS

Solidification/stabilization as used in this study represents a method of reducing the pollutant potential of POTW wastes when they are disposed of in landfills. But much more study is required before the long-term effects of such practices can be determined and adequately evaluated. Actual field tests using large-scale processing equipment and treated sludge samples may show that the material behaves differently from the small samples in this study. Large-scale controlled tests using treated waste samples that have surface-to-volume ratios more typical of those actually encountered in landfill situations are needed to give a more realistic estimate of treatment benefits. Intermittent saturation of the treated samples in contrast to continuous submersion should also be considered in any future testing. In addition, small batch waste processing may not accurately reflect the commercial-scale treatment procedures.

This study incorporated treatment processes with completely different physical and chemical bases. Further tests need to be made within each overall type of treatment process to judge better the effectiveness within each process type. Perhaps comparison of selected physical properties with leaching characteristics within each process type might reveal those properties of the treated products that have predictive value in assessing their pollutant potential.

The development of a standardized leaching test is necessary to facilitate valid comparisons and to increase the predictive value of bench-scale leaching tests. A standardized leaching test should mimic the conditions under which maximum leaching takes place (i.e., short-term test, small sample size, aggressive leaching liquid, particulate containment for non-solidified samples).

SECTION 4

METHODS AND MATERIALS

SOURCES, SELECTION AND DESCRIPTION OF POTW WASTES

The wastes used in this study represent typical types of residual material produced in POTW operations (incineration and anaerobic/aerobic stabilization). These POTW wastes were obtained from two wastewater treatment plants--an ash from a rotating-hearth incinerator, and a dried sludge from the drying bed associated with the operation of an Imhoff digester tank. Both treatment plants receive industrial wastes that contain heavy metals, and the wastes used in this testing program create some disposal problems resulting from elevated metal levels. A listing of the sludges studied is included in Table 1 along with the code used to identify each sludge type and treatment process.

Untreated Sludge Composition

The two sludges tested are representative of typical wastewater treatment sludges. The results of chemical analyses of the two sludges for selected constituents are given in Tables 2 and 3. The sludges were dried, weighed, digested in hot 8N nitric acid and analyzed for those constituents to be followed in the leach tests. Testing procedures generally followed EPA standard techniques (USEPA, 1976b, 1980b). The constituents to be determined were the same for all samples and were chosen on the basis of previous studies as important indicators of leaching activity.

The untreated sludges were compacted using a hydraulic press to produce the sample to be loaded and leach tested. No water was removed during this process. The sample was totally submersed in the leach liquor; consequently, the rate of leaching should be proportional to the amount of the constituents on the surface available to be leached, the solubility of the constituent, the rate of internal diffusion to the surface of the sludge, and the time of leaching. Imhoff sludge had a higher water and total organic carbon content than the incinerator ash. Those volatile constituents such as arsenic, cadmium, selenium, zinc, and sulfate were in lower composition in the ash as compared with the Imhoff sludge. On a dry weight basis, the metals, cadmium, chromium, selenium, copper, iron, and zinc were all in significantly lower amounts in the ash than in the Imhoff sludge. Only manganese appeared at higher concentrations in the incinerator ash.

TABLE 1. LIST OF POTW WASTES STUDIED, DESIGNATION IN THIS STUDY, AND SOLIDIFICATION/STABILIZATION PROCESS EMPLOYED

Waste type	Waste designation	Solidification/stabilization process employed
Imhoff digestion	RI	No treatment
	XA	Cement/soluble silicate (optimized formula)
	XB	Cement/soluble silicate (cost effective formula)
Incinerator ash	RA	No treatment
	X	Cement/soluble silicate
	Y	Pozzolan cement (lime and fly ash additives)
	Z	Gypsum-based material (sulfate/lime additives)

TABLE 2. CHEMICAL COMPOSITION OF TREATED AND UNTREATED IMHOFF SPECIMENS

Parameter	Untreated Imhoff sludge (RI) (mg/kg)	Process X Treatment A (XA) (mg/kg)	Process X Treatment B (XB) (mg/kg)
As	17.4	9.3	10.9
Cd	213.0	26.6	88.7
Cr	3,060	397	1,330
Cu	1,370	170	598
Fe	22,600	10,500	16,100
Pb	1,130	142	486
Mn	283	99	180
Se	2.65	0.42	0.51
Zn	4,140	579	1,800
SO_4	1,880	19,400	18,950
CI	333	263	575
TOC	127,000	40,300	61,600

NOTE: Samples of each treatment process were digested and analyzed independently. All on dry weight basis.

TABLE 3. CHEMICAL COMPOSITION OF TREATED AND UNTREATED INCINERATOR ASH SPECIMENS

Parameter	Untreated incinerator ash (RA) (mg/kg)	Process X (X) (mg/kg)	Process Y (Y) (mg/kg)	Process Z (Z) (mg/kg)
As	13.4	10.9	12.6	9.2
Cd	2.26	1.36	2.35	1.48
Cr	566	324	677	461
Cu	750	497	840	523
Fe	16,800	14,500	19,800	13,800
Pb	1,160	768	1,180	638
Mn	783	519	875	553
Se	0.20	0.18	0.24	0.32
Zn	705	451	863	568
SO_4	6,200	8,600	5,200	238,000
Cl	455	265	230	240
TOC	1,700	3,500	2,900	2,560

NOTE: Samples of each treatment process were digested and analyzed independently; all in mg/kg dry weight of final product.

SELECTION OF SLUDGE PROCESSORS

In the initial phase of this project, seventeen companies who were developing or offering commercial waste-treatment processes were contacted with regard to participation in the POTW waste treatment evaluation project. Three vendors ultimately agreed to prepare materials for testing. A sufficient sample of each waste type was obtained for WES laboratory testing program.

Stabilization Techniques

Each sludge was thoroughly mixed and sampled using a standard sampling procedure (ASTM, 1973;) so that uniform samples would be provided to each processor. The sludges were partitioned into several subsamples: One portion was used for preliminary evaluation by the processors; a second portion was used for untreated sludge chemical and physical testing; a third portion was utilized for the actual sludge solidification; and the remainder was retained for any supplementary testing. Sludge samples were stored in sealed, plastic containers and maintained at room temperature (22°C).

The solidification/stabilization processes used in this project generated some products which shrunk when cast into standard concrete molds. In order

to obtain specimens of known dimensions, it was necessary to core larger cast blocks of the hardened/treated sludges after they had been allowed to cure.

A brief summary of the procedures used is given below and a summary of formulation and leach vessel loading are presented in Table 4. Specific information on the additives used by each processor is not given as the formulations are proprietary; only the general category of each additive is given when known. These figures are taken from data supplied by the vendors.

Processor X--

Processor X, who was the only processor to treat both types of sludges, was responsible for Treatments XA, and XB on the Imhoff sludge, and Treatment X on the incinerator ash. In all cases, the mixing procedure was identical. For Processor X, the waste and water were mixed in a 1.7-cubic-meter cement mixer for 10-15 minutes to produce a slurry for processing. The proprietary dry reagent (cement and other materials) was added and mixed for about 3 minutes. The mixture was then circulated for an additional 3 minutes using a centrifugal pump. This approximated the technique used for normal, full-scale processing procedures. A liquid reagent was added and mixed for

TABLE 4. FORMULATION AND LEACHING SAMPLE COMPOSITION FOR TREATED AND UNTREATED SEWAGE TREATMENT PLANT WASTE

Sludge and process code	Formulation			Core* weight (g)	Dry solids (%)	Dry Solids in core (g)
	Dry sludge solids (%)	Treatment reagents (%)	Water (%)			
Imhoff sludge						
RI	57.6	--	42.4	121.2	57.6	69.9
XA	5.5	26.0	68.5	104.8	63.4	66.4
XB	15.8	17.7	66.5	105.2	62.3	65.5
Incinerator ash						
RA	77.2	--	21.8	67.4	77.2	52.0
X	20.6	11.3	68.1	106.0	58.7	62.2
Y	(58)†	(3)	(39)	134.3	65.1	87.4
Z	20.00	15.6	64.4	132.7	51.2	67.9

* Average of three cores used in leaching experiment. Variations in weight of less than 5% were typical. Weights of dry solids in core includes hydration water.

† Formulation for Process Y not known due to unspecified water additions. Numbers given are estimated from chemical analyses and information supplied by vendor.

about 3 minutes or until the mixture appeared pumpable. The mix was recirculated briefly to clear the pump and was pumped into the molds. The relative proportions of materials used by this treatment process were as follows:

Treatment XA--The mix ratio for Treatment A was 19.7 kg of Imhoff sludge to 131.7 kg of water to 53.1 kg of reagents.

Treatment XB--The mix ratio for Treatment B was 50.4 kg of Imhoff sludge to 100.8 kg of water to 32.6 kg of reagents.

Treatment X--The mix ratio for Treatment X was 52.7 kg of incinerator ash to 122.6 kg of water to 22.4 kg of reagents. After pumping, the molds filled with treated waste were covered with plastic and set aside to cure.

Processor Y--

The mixes were prepared in a 0.40-cubic meter, turbine mixer. The amount of additive used in the mixes was 5% of the dry sludge solids. After all batches were adjusted to "optimum moisture" with an unspecified amount of water, the material was manually compacted into molds with the aid of a 5.6-kg circular tamper. The edges of the boxes were compacted with a 5- by 10-cm block of wood and a hammer. After compaction, the boxes were wrapped in plastic to prevent moisture loss during curing.

Process Y added considerably less water and additive materials (flyash and lime) to the ash than the other processors which gave a drier product with much higher sludge-solids in it. Although the figures in Table 4 are only best estimates, they are borne out by bulk analyses of final products.

Processor Z--

Processor Z was responsible only for Treatment Z on the incinerator ash. The mixing of ash, water, and reagents by Processor Z was by means of a propeller mixer. For each 30.2 kg of ash, 60.5 kg of water was added and mixed to make a slurry. While mixing, 10.6 kg of liquid reagent was added and mixing continued for 1 hour to dissipate the considerable heat that is generated. Finally 7.55 kg (dry weight) of solid reagent (in 7.55 kg water) was added to the mix and mixing continued for an additional 30 minutes to produce a plaster-like material. The residue was then placed in containers to settle. The treated waste was filtered to remove excess water and compacted in a mold. The waste tended to dry to a putty-like material with very little setting or hardening occurring.

LEACH TEST DESIGN

The primary concern in ultimate disposal of POTW wastes is the rate of pollutant migration into the surrounding groundwater (Geraghty and Miller, Inc., 1978; Robson, 1977). Consequently, the leaching tests in this study were designed to simulate leaching from sludges buried in an unlined, water-saturated landfill. This leaching test is aimed at measuring the rate of pollutant movement into an aqueous medium under conditions closely simulating those encountered in the field. Specifically, the major objective of the leach testing was to compare the rates of loss of contaminants from the two untreated wastes and from wastes that were chemically solidified or stabilized.

The leaching apparatus, shown schematically in Figure 1 and in use in Figure 2, allows such parameters as contact time, surface area, and quantity of leaching liquid to be controlled. While the leaching medium was changed daily (except weekends), samples for chemical analyses (Table 5) were taken weekly for the first month, biweekly for the next month, and monthly thereafter. Total leaching time was 90 days. All leaching vessels were maintained and sampled in triplicate. A total of 192 leachate samples were generated for each test. The leach vessel was constructed of materials that were inert with respect to the waste specimens and leaching liquid. The test vessel was made of a 180-mm length of 155-mm plexiglass tubing. The test specimen, a 50 by 50-mm right cylinder, was supported in the leaching liquid (CO_2-saturated deionized water) in 60 by 150-mm cellulose extraction thimble which was supported both at the base and at the top. The bottom of the test vessel was sealed and a Teflon valve stopcock provided for sampling the leach liquid. After daily removal of all of the leaching liquid, the liquid was replaced with 1 liter of fresh, carbon dioxide-saturated water through the intake in the lid.

The leaching fluid used in the testing was deionized water saturated with carbon dioxide (pH 4.0 to 4.2). All materials used in the leach fluid distribution system were either polypropylene or Teflon to minimize any contamination during the testing.

The treated and untreated waste in the form of cylindrical cores were placed into the cellulose thimble in the leaching vessel. Due to the texture of the samples (some crumbly with soft and hard areas) it was difficult to obtain smooth-sided samples. The cylinders of untreated sample of Imhoff sludge and incinerator ash were prepared by pressing aliquots of waste into a 5- by 5-cm metal die using a small pellet press. The test specimen volume was 98 cm^3; the surface area of the test specimen was 117.8 cm^2 and the surface-area-to-volume ratio was 1.2 cm^{-1}.

Two types of experimental controls were incorporated into the leaching test. One type of control consisted of monitoring the leachate fluid in the reservoir for the parameters tested. A second control consisted of leachate vessels maintained in triplicate without sludge and sampled at the appropriate times (blank vessels). Corrections were made for background effects of the leach fluid and column apparatus by subtracting the values of the blanks from the experimental values. In all cases these blank corrections were insignificantly small.

The actual weight of samples loaded into each of the leach vessels along with the weight and percent of dry sludge solids in the product, are shown in Table 4. Also given are the percentages of water, treatment reagents, and dry sludge solids which were incorporated into the final products. Process X had only 5 to 20% W/W of dry sludge solids in their final product; Process Z had 20%.

CHEMICAL ANALYSES

Leachate samples were analyzed periodically using a sampling sequence similar to the International Atomic Energy procedure for leaching solidified

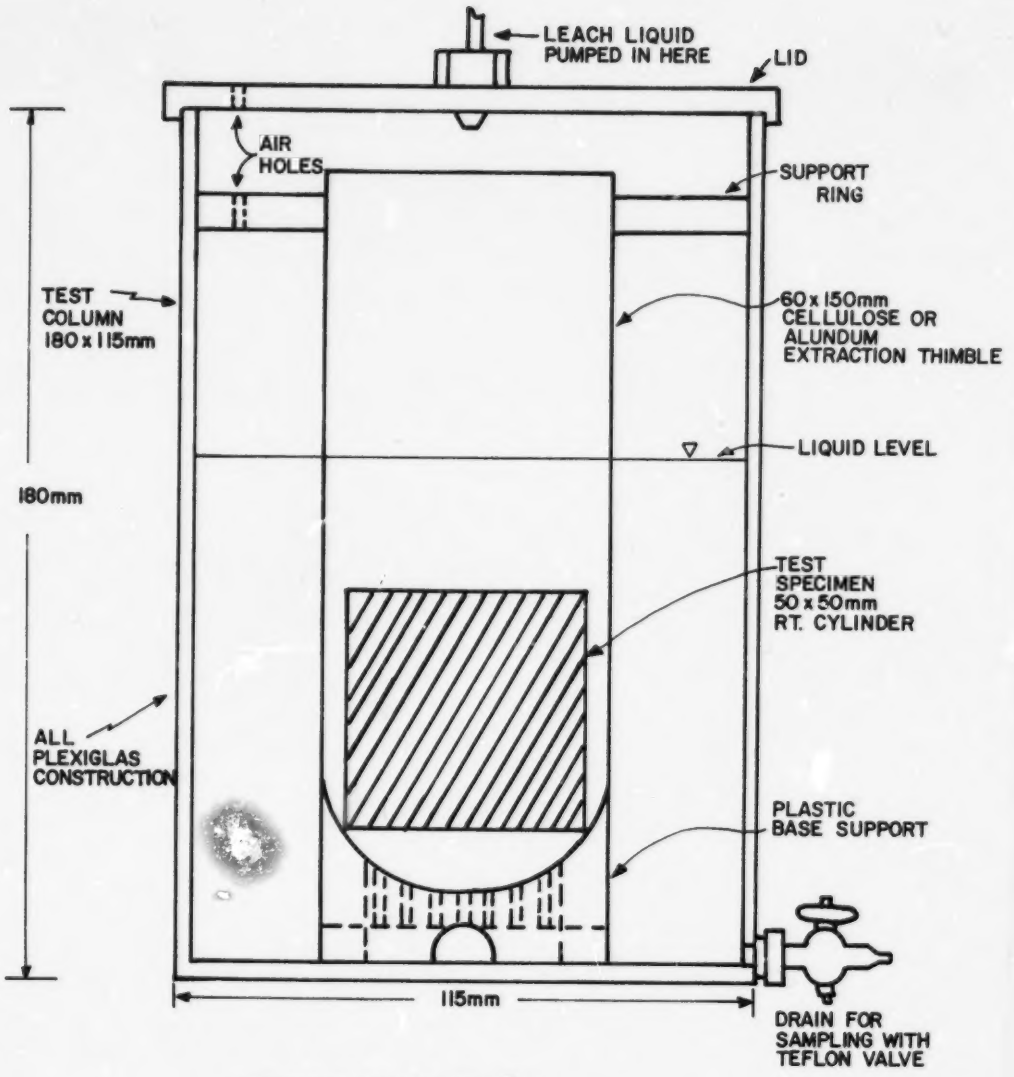

Figure 1. Design of leaching apparatus.

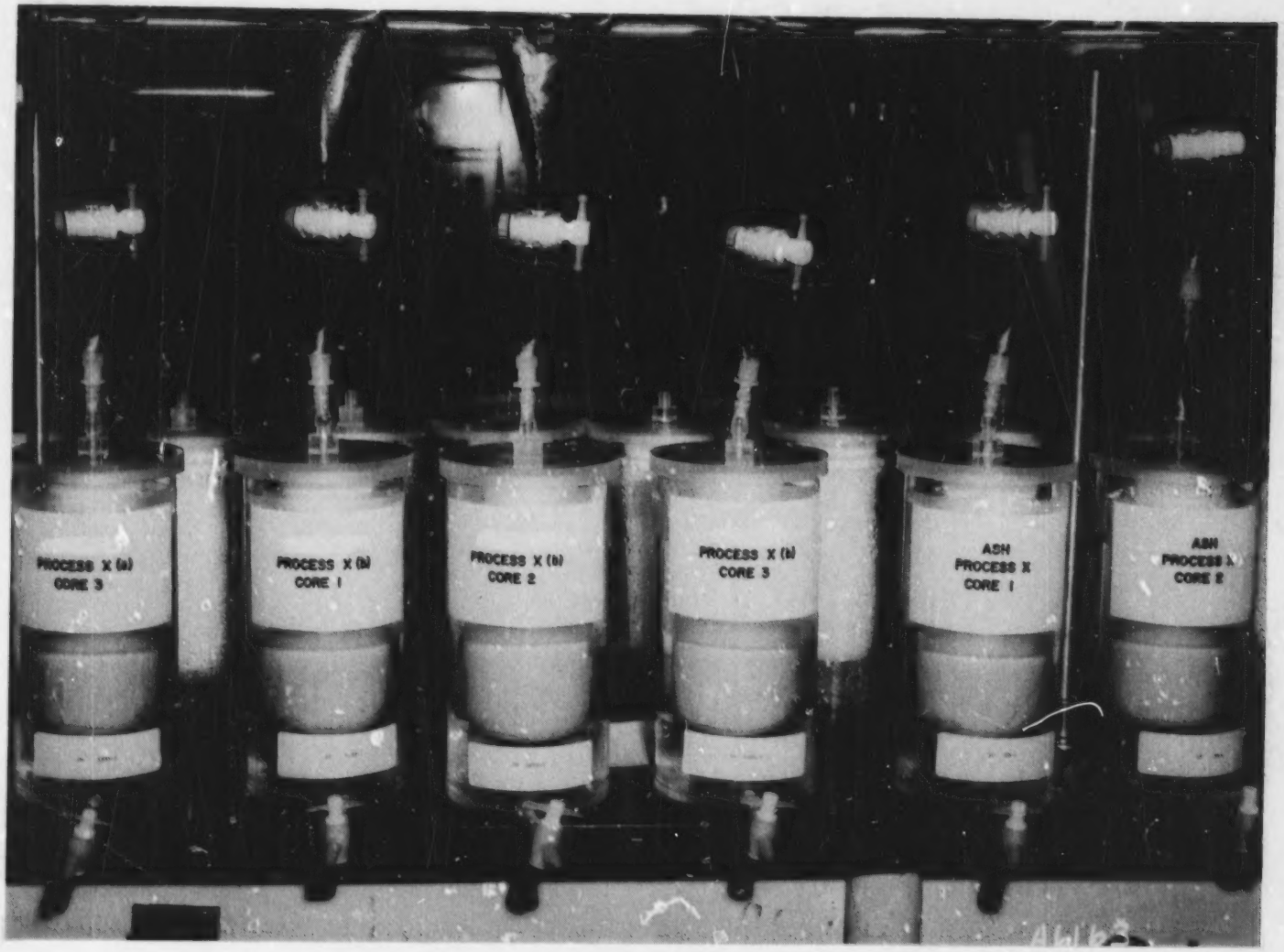

Figure 2. Leaching apparatus in use on samples XA, XB, and X treated products.

TABLE 5. SCHEDULE FOR SAMPLING FOR CHEMICAL ANALYSES

Waste and process code	Relative sampling time (Days since initiation of leaching)
Imhoff sludge	
RI	1, 8, 15, 22, 30, 45, 60, 88
XA	1, 8, 15, 22, 29, 45, 59, 90
XB	1, 8, 15, 22, 29, 45, 59, 90
Incinerator ash	
RA	1, 8, 15, 22, 30, 45, 60, 88
X	1, 8, 15, 22, 29, 45, 59, 90
Y	1, 8, 15, 22, 30, 45, 59, 91
Z	1, 8, 15, 22, 30, 45, 59, 91

radioactive wastes (International Atomic Energy Agency, 1971). On each analysis date (Table 5), after the pH and conductivity were measured, the leachate samples were split into aliquots of appropriate volume for determination of metals, anions, and TOC. Each aliquot was preserved using EPA-accepted techniques (U. S. Environmental Protection Agency, 1976b). Details of sample preservation are given in Table 6. All samples were maintained at 4°C until analyzed by accepted EPA techniques. Parameters selected for analysis (metals, anions, total organic carbon, pH, and conductivity), limits of detection, and the method of analysis are given in Table 7.

TABLE 6. METHODS OF PRESERVATION OF LEACHATE SAMPLES

Parameter	Weekly sampling day	Method of preservation
TOC	Midweek	5-ml samples placed in a glass tube with a screw cap and Teflon liner, refrigerated
SO_4, Cl	Midweek	Aliquots placed in 500-ml BOD bottle with no preservative
Metals	Midweek	100-ml aliquots taken in plastic bottles with 1 ml of ultrapure HNO_3 (final pH 2.0)
pH	Daily M-F	None (determined immediately)
Conductivity	Daily M-F	None (determined immediately)

TABLE 7. PARAMETERS ANALYZED AND LIMITS OF DETECTION

Parameter	Method of analyses or instrument	Limit of detection
Arsenic (As)	Perkin-Elmer HGA* Atomic Absorption	0.01 mg/ℓ
Beryllium (Be)	Spectrametrics Argon Plasma Emission, Spectrophotometer Model II	0.005
Cadmium (Cd)	HGA Atomic Absorption	0.0001
Chromium (Cr)	HGA Atomic Absorption	0.001
Copper (Cu)	HGA Atomic Absorption	0.001
Iron (Fe)	Spectrametrics Argon Plasma Emission, Spectrophotometer Model II	0.05
Lead (Pb)	HGA Atomic Absorption	0.001
Manganese (Mn)	Spectrametrics Argon Plasma Emission, Spectrophotometer Model II	0.001
Selenium (Se)	HGA Atomic Absorption	0.01
Zinc (Zn)	Spectrametrics Argon Plasma Emission, Spectrophotomer Model II	0.05
Chloride (Cl)	Manual Titration	5.
Sulfate (SO_4)	UV-Visible Spectroscopy	8.
Total Organic Carbon (TOC)	Dohrmann, DC-50, Carbon Analyzer	1.0
pH	Electrometric pH meter	0.01 units
Conductivity	YSI Model 31 Conductivity Bridge	0.5 μmho/cm

* HGA = heated graphite atomizer.

Sampling and determinations of pH and conductivity were conducted daily, Monday through Friday. A peak in leachate conductivity was observed each Monday and the conductivity values typically decreased until Friday. Presumably this peak of conductivity was due to the accumulated leaching loss over the two days of the weekend when the leaching liquor was not changed. The samples for metal and anion analyses were taken at midweek. Since the conductivity values at midweek were midway between the high and low values for the week, they were considered to be representative values and to correct for this weekly variation.

Determination of initial amounts of metals, chloride, fluoride, and sulfate were made on nitric acid digests of a subsample from each waste. The metals chosen to be determined in the leachate during the 90-day leaching test were limited to those toxic metals found to be in significant concentration in the waste. Moisture content (Table 4) was determined from a second subsample of each waste material.

A listing of the composition of each treated and untreated waste is given in Tables 2 and 3. The total amount of each constituent which is available to be leached from each test sample is given in Tables 8 and 9. These values represent the composition of each waste in dry solids (i.e., corrected for the variable amounts of moisture in each waste). This correction was made by multiplying the concentration of each constituent in the waste (in mg/kg) by the dry weight of the waste sample (kg) to determine the final amount of each constituent present in each leaching specimen (Table 4). These values were used to determine the fraction of each of the constituents leached from each sample.

PHYSICAL TESTING

Physical testing of treated samples was performed to assess the strength, durability, trafficability, and other engineering properties of the different

TABLE 8. AMOUNT OF EACH CONSTITUENT IN THE LEACH TEST SAMPLES OF IMHOFF SLUDGE (TREATED AND UNTREATED)

Parameter	Untreated Imhoff Sludge* (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
As	1.22	0.614	0.715
Cd	14.8	1.76	5.82
Cr	214.2	26.4	87.1
Cu	95.6	11.3	39.2
Fe	158	698	1060
Pb	79.0	9.44	31.9
Mn	19.7	6.58	11.80
Se	0.18	0.028	0.034
Zn	289	38.5	118
SO_4	1310	1290	1240
Cl	23.3	17.4	37.7
TOC	8320	2660	4040

* All values are in milligrams. Each value is average of three replicate samples loaded into replicate leaching vessels. Variations of less than 5% in speciment weight were typical.

TABLE 9. AMOUNT OF EACH CONSTITUENT IN THE TEST SAMPLE OF INCINERATOR ASH (TREATED AND UNTREATED)

Parameter	Untreated incinerator ash* (RA)	Process X (X)	Process Y (Y)	Process Z (Z)
As	0.695	0.679	1.10	0.625
Cd	0.118	0.085	0.212	0.101
Cr	29.4	20.2	39.2	31.3
Cu	39.0	30.9	73.4	35.5
Fe	874	902	1730	941
Pb	60.6	47.8	103.0	43.3
Mn	40.7	32.3	76.5	37.5
Se	0.010	0.011	0.021	0.022
Zn	36.7	28.1	75.4	38.6
SO_4	323	535	455	16,200
Cl	23.7	16.4	20.1	16.3
TOC	88.5	218	254	174

* All values are in milligrams. Each value is the average of three replicate samples loaded into replicate leaching vessels. Variations of less than 5% in specimen weight were typical.

treated materials. A comparison of these physical properties gave an estimate of the improvement in physical characteristics provided by the different stabilized/solidified wastes and the durability of these new waste forms under normal surface weathering.

Ten-centimeter-diameter cores of treated wastes were submitted for physical testing. Moisture content, unconfined compressive strength, cone penetration, freeze-thaw, and wet-dry tests were completed for cores taken from blocks cast by each processor. The coring procedures used to obtain the cores from cast blocks of treated materials varied with the different physical properties of the treated material. The treated ash sludge of Process Z did not set, was of a mud-like consistency, and slumped. The materials resulting from Processes XA, XB, and X set, but were more soil-like than concrete-like. The Process Y samples resembled soft concrete. Process Z cores were obtained by manually pushing a 10-cm-diameter tube through the cast treated material. Process Y cores were obtained using a diamond-studded 10-cm-core barrel and a rock-boring machine. Compressed air was used to flush drill cuttings. Cores from material from Processes XA, XB, and X were obtained by pushing a 10-cm ID steel tube through the cast material with a hydraulic press.

Unconfined Compressive Strength

Unconfined compressive strength tests were performed on samples treated by Processes XA, XB, X, and Y. The test procedure determines the uniaxial, unconfined strength of a cohesive or cemented material by loading a cylindrical specimen axially until failure. The highest compressive stress sustained is considered the unconfined compressive strength of the sample. The test procedure is found in Appendix XI of EM 1110-2-1906 (U. S. Department of the Army, 1970) and in ASTM D 2166-66 (ASTM, 1973).

Cone Penetration

Cone penetration was determined using a cone penetrometer on prepared cores. The hardness of the sample and trafficability over the material is inferred from the distance by which the cone penetrated the sample using a given uniform pressure. The test procedure is described in Karafiath and Nowatski (1978).

Durability Testing

Two testing procedures, freeze-thaw (ASTM Test D560-57; ASTM, 1973) and wet-dry (ASTM D559-57; ASTM 1973) were used to determine the physical stability of the treated sludges and therefore to predict the durability of the treated material under the typical weathering conditions encountered after disposal. Samples were prepared for freeze-thaw testing by taking 10- by 10-cm right cylinders from the cored samples, freezing for 24 hours at -23°C and then thawing at 21°C for 23 hours. Loose material was removed from the cores by brushing thawed samples with a stiff wire brush. Samples for wet-dry testing were the same size as for freeze-thaw tests. Samples were submerged in clean, potable water for 5 hours, removed and dried in an oven at 71°C for 42 hours, and subsequently cleaned with a wire brush. Results of both tests are reported as percent weight loss after 12 cycles or number of cycles until disintegration, whichever occurs first.

Moisture Content

The moisture content of the test samples was determined by change in weight after drying at 105°C for 24 hours. This result is expressed as a ratio of the weight after drying to the weight before drying expressed as a percent.

SECTION 5

RESULTS

GENERAL CHARACTER OF TREATED AND UNTREATED TEST SPECIMENS

The untreated wastes as supplied were dry, fine-to-coarse-grained, powdery materials. The Imhoff digestor waste had a grey-greenish color and a soft, feltlike character and an earthy odor typical of a dried anaerobic digestor bottom sludge (Figure 3). The raw sludge had a density comparable to moist soil and contained identifiable objects such as rubber bands, cigarette filters, etc. The compressed specimens produced for leach testing were stable and held their shape well. The incinerator ash was orange-brown in color and had a typical ashlike texture (Figure 4). The grain size was quite variable with a high proportion of pebble-sized clinkers. The compressed specimens were easily crumbled, did not hold up well, and were of low density.

Treated sludge specimens resulting from Treatment Processes X, XA, and XB showed cracks on the sides of the cast but not on the tops and bottoms. The casts required delicate handling procedures because the material easily broke or sloughed from touch. The solidified material from Imhoff sludges was very soft; the solid product made from incinerator ash had less cracking and was more durable. Sludge resulting from Treatment XB was denser and showed less cracking than the sludge resulting from Treatment XA. Because of the nature of these sludges produced by Treatment Processes X, XA, and XB, the treated specimens were crumbly with soft and hard spots, making it difficult to obtain an intact specimen of the required sizes for testing purposes.

Solid materials resulting from Treatment Process Y were hard and resembled low-strength concrete. Solid wastes resulting from Treatment Process Z remained wet and did not harden or set.

RESULTS OF PHYSICAL TESTING

Physical testing of samples was performed to assess the strength and durability of the treated materials as compared with the untreated samples. A comparison of the physical properties allows for a judgment to be made about the relative ability of the treatment processes to improve the handling characteristics of the waste materials and provide durable materials suitable for landfilling.

Moisture Content

The free moisture content of the treated and untreated sludges is presented in Tables 10 and 11. In general the untreated Imhoff sludge had a

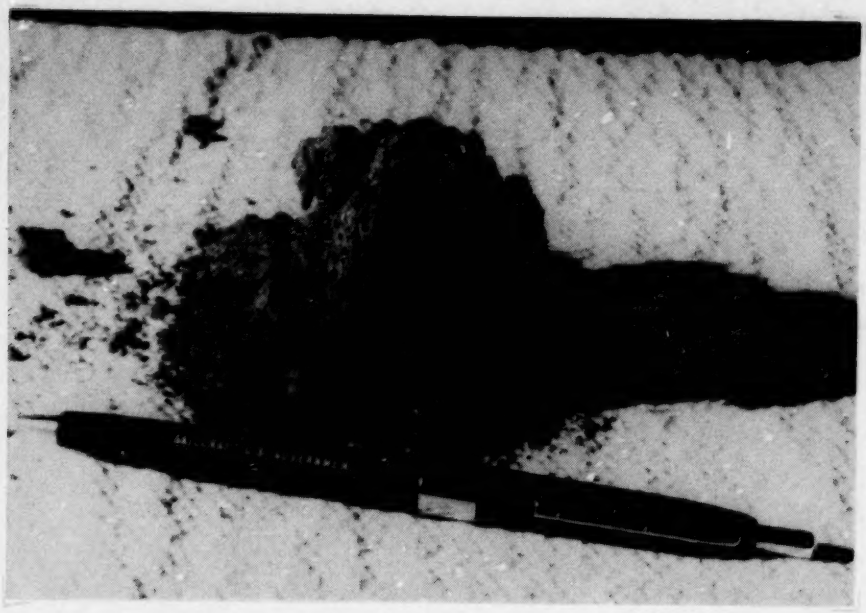

Figure 3. Photo of Imhoff digester sludge showing the felt-like texture of the material.

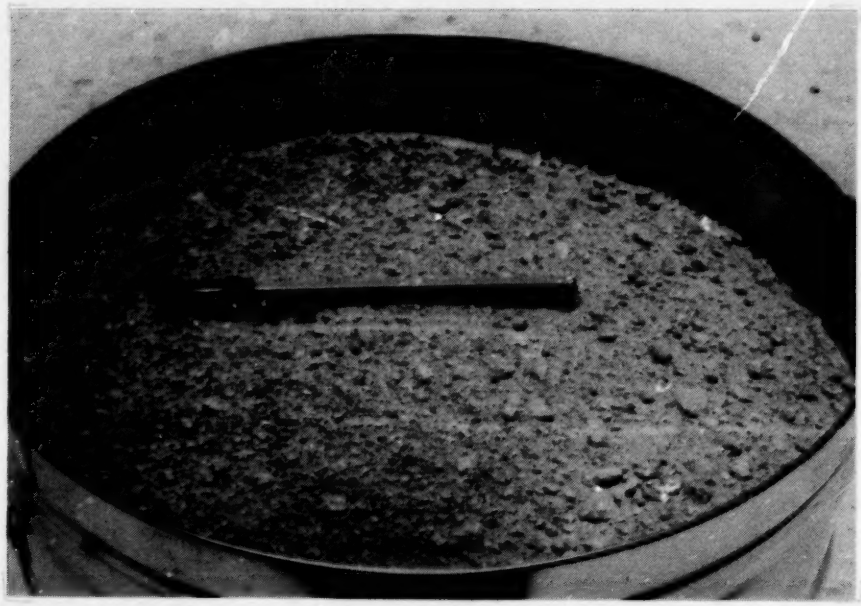

Figure 4. Photo of the sludge incinerator ash.

TABLE 10. SUMMARY OF PHYSICAL PROPERTIES OF IMHOFF SLUDGES (TREATED AND UNTREATED)

Physical property	Untreated Imhoff sludge (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
Moisture content (%)	42.3	36.6	37.7
Cone penetrometer reading (cm)			
Center	ND*	0.8	0.8
Edge	ND	1.4	†
Unconfined compressive strength			
Load (N)	ND	100.8	114.3
N/cm^2	ND	24.3	27.6
Durability Tests (cycles to destruction)			
Freeze/thaw	ND	2	2
Wet/dry	ND	2	2

* Not done for this sample.

† Sample fractured.

TABLE 11. SUMMARY OF PHYSICAL PROPERTIES OF INCINERATOR ASH (TREATED AND UNTREATED)

Physical property	Untreated incinerator ash (RA)	Process X (X)	Process Y (Y)	Process Z (Z)
Moisture content (%)	22.8	41.3	34.9	49.8
Cone penetrometer reading (cm)				
Center	ND*	0.4	ND	ND
Edge	ND	1.4†	ND	ND
Unconfined compressive strength				
Load (N)	ND	118.1	169.9	ND
N/cm^2	ND	25.5	41.6	ND
Durability tests (cycles to destruction)				
Freeze/thaw	ND	2	11	ND
Wet/dry	ND	2	5	ND

* Not done for this sample.

† Sample fractured.

higher moisture content than did the untreated incinerator ash (42.3% compared with 22.8%). Treatment procedures XA and XB lowered the free moisture content of the Imhoff sludge by between 5% and 10%. The treatment processes used for the incinerator ash increased the moisture content of the resultant solid waste samples. The highest moisture content was for the samples resulting from Process Z (49.8%), the lowest in materials treated by Process Y (34.9%). The moisture content of sludges treated by Process X was 41.3%.

Cone Penetration

Only waste samples made using Processes X, XA, and XB were tested. The results are presented in Tables 10 and 11. The penetrability of the treated Imhoff sludges was slightly greater (as measured in the center of the specimen) than that of the treated incinerator ash, indicating that the ash produced a harder product. There was no difference between the penetrability of the two Imhoff samples of different treatments (XA and XB) although XB had greater strength.

Samples from Process Z were too wet for application of any physical testing techniques. Cone penetrometer readings were not made on samples treated by Process Y as they were too hard for meaningful data.

Unconfined Compressive Strength

Samples produced by Treatment Processes X, XA, XB, and Y were tested to determine unconfined compressive strength. Untreated samples were not tested. The results are presented in Tables 10 and 11. The two treatments used in processing the Imhoff sludge produced solid wastes having similar strength. The load required for specimen collapse was not significantly different for the two sludges. However, two of the processes used for treatment of incinerator ash produced widely different results. The Treatment Process Y produced specimens with higher compressive strengths than Treatment Process X (see Figures 5 and 6). The load required for specimen failure with Y was greater (169.9 N) than for the sample treated by Process X (118.1 N). The samples of Process Z were too wet and structurally weak for application of the unconfined compressive strength test. The materials slumped when the test specimen was placed in the hydraulic press.

Durability Tests

Two testing procedures, freeze-thaw and wet-dry, were used to assess the long-term physical durability of the solidified wastes under simulated field conditions. The solidified products used in this study were designated specifically for disposal in land fill operations where the samples would be buried above the water table, and below the level of frost penetration. The freeze-thaw and wet-dry tests are considered to be accurate indicators of product durability, but they do represent worst-case conditions in landfilling. They are useful only in determining the relative durability of the solidified sludges produced by the processes used in this study.

For the freeze thaw test, fully cured, solidified sludge samples were subjected to the standard freezing and thawing test used for compacted soil-cement mixtures. Performance in the test is evaluated by weight loss during the test or by the number of cycles necessary to cause disintegration of the sample. The wet-dry test is similar to the freeze-thaw test, but is designed to be a much less severe treatment of the test samples. Results of both durability tests are given in Tables 10 and 11. The sludges produced by Process Z were too wet for durability testing and testing of untreated wastes was not attempted because they could not be made into durable solids.

Only the wastes treated by Process Y survived over 3 rounds of freeze-thaw testing. Samples treated by Processes X, XA, and XB were destroyed in the second round of testing; however, the samples produced by Process Y survived 11 cycles. Pictures of test specimens after one and two cycles are shown in Figures 7 and 8. In the wet-dry testing procedure the sample produced by Process Y survived 5 cycles before being destroyed; the samples treated by Processes X, XA, and XB were destroyed in the second cycle of thawing. There appears to be little difference in the durability of the Imhoff residues treated by Process XA and XB; however, Process Y produced a solid waste with greater durability than that produced in Process X.

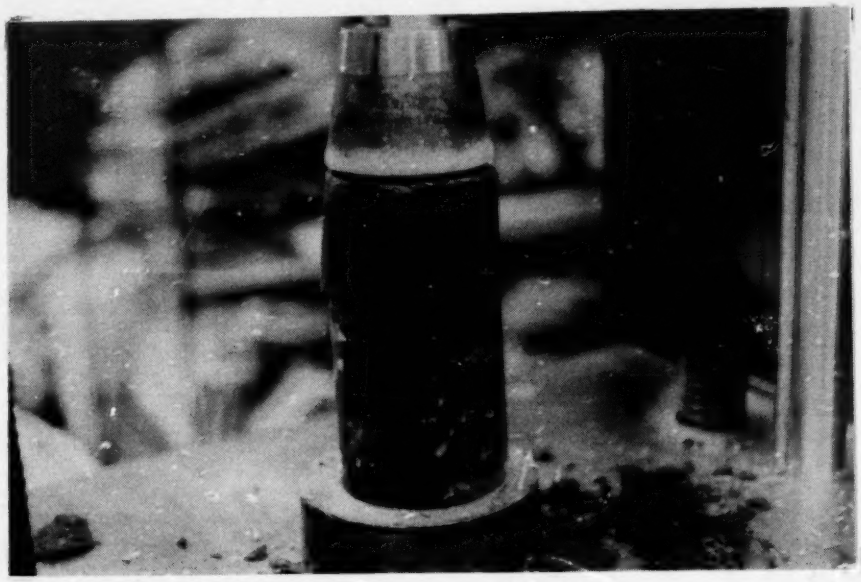

Figure 5. Specimen of Process X-treated incinerator ash after failure.

Figure 6. Specimen of Process Y-treated incinerator ash after failure.

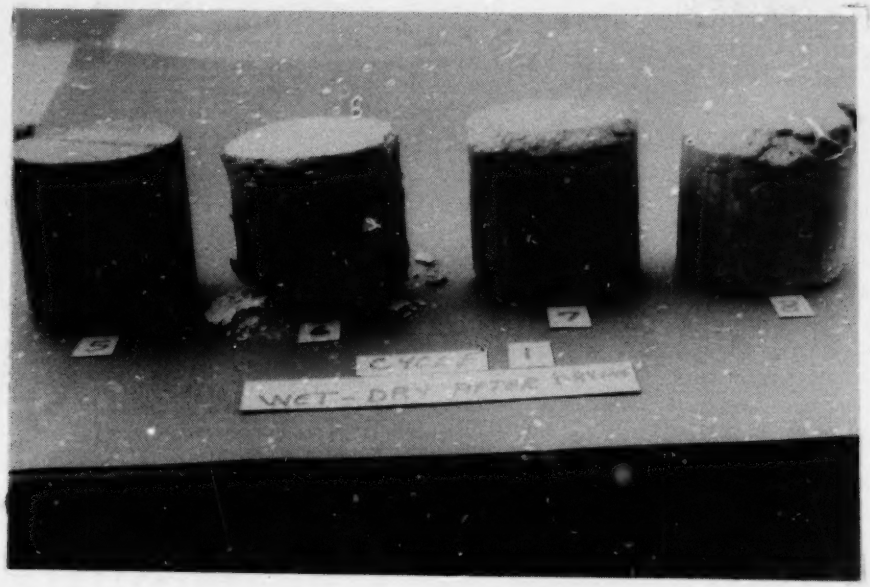

Figure 7. Specimen in wet-dry test after one cycle.
(right to left: XA, XB, X and Y)

Figure 8. Specimens in wet-dry test after two cycles.
(Clockwise from #5 at top: Y, X, XA)

RESULTS OF LEACH TESTING

Leaching Test Controls

Two types of controls were maintained for the leaching loss tests. For the first control, measurements of all metals, anions, total organic carbon, pH, and conductivity were made on the reservoir liquid entering the leach vessels (carbon dioxide-saturated, deionized water). This liquid from a common reservoir was used as the leaching medium in all leach vessels. The values obtained for the variables listed above were subtracted from the experimental values obtained for the one-liter leach sample taken from each vessel. This process corrected for any constituents derived from the leaching medium rather than leaching from the sample being tested. This correction for the reservoir liquid was negligible.

The second control was a series of empty (containing no test specimen) leach vessels. Therefore any constituents which might be derived from the leach vessel and associated apparatus could be determined. The blank leach vessels were maintained in triplicate as were the experimental leach vessels. The values for metals, anions, total organic carbon, pH, and conductivity for the one-liter samples taken from the blank vessels did not differ significantly from the values obtained from the reservoir leaching fluid. Weekly mean values for conductivity and pH for empty vessel controls are presented in Table 12. Metals, anions, and total organic carbon concentrations for these blanks (all three replicates) are given in Appendix A.

Patterns of Waste Constituent Leaching

The leach tests were designed to define quickly and accurately the potential loss of constituents from treated and untreated wastes. The waste sample was small in size and completely submersed in the leaching liquid (deionized water saturation with carbon dioxide). The leaching liquid (1 ℓ) was drained and changed daily (except weekends). Only one treatment process (Process Y) produced a structurally competent solid. The other waste samples were soil-like (RI, RA, X, XA, XB) or wet and plastic (Z). Consequently, the samples frequently broke apart or sloughed in the cellulose extraction thimbles. Fragmentation of samples during testing increased the surface area of many specimens and accelerated losses during leaching. Suspended materials were confined to the cellulose thimble and therefore were not present in the leachate samples. All the constituents lost to the leaching fluid in this test procedure were in solution in the leachate.

Chemical factors such as solubility, diffusion, and adsorption/desorption appeared to be the major factors influencing the leaching behavior of the materials in the vessel in this study. The leaching vessel design and the small sample size allowed the test sample to be completely and constantly submerged and the leach liquor to be completely replaced during testing; therefore, the leach rate of each constituent should be a function of factors such as the solubility and diffusion rates, and the amount of each constituent in the specimen available for leaching. Biological factors were not controlled as the relatively short test period (90 days) and the low organic carbon

TABLE 12. AVERAGE WEEKLY pH AND CONDUCTIVITY VALUES FOR BLANK VESSEL LEACHING TEST

Midpoint (day)	Number of values	pH	Conductivity* (μmho/cm)
0	9	3.7	- 2
7	12	3.9	17
14	15	4.1	-14
21	15	4.1	-16
28	15	4.0	-15
35	15	4.0	-12
42	12	4.1	-15
49	12	4.0	-11
56	15	4.2	-10
63	15	4.2	- 9
70	15	4.2	-12
77	15	4.1	-10
84	15	4.1	-10

* Conductivity corrected for reservoir blank.

content (especially of the ash) minimized any biological activity. No evidence of pronounced biological activity was noted.

The leaching loss data for the metals, anions, and total organic carbon for all blank, untreated, and treated sludge vessels are included in Appendix A. The daily pH and conductivity values are presented in Appendix B.

Three patterns of leaching appear in the constituents of untreated sludges studied here. For constituents that are highly soluble most leaching takes place in the initial days of the test and the concentration in the leachate rapidly drops to a constant low value. Chloride and sulfate show this pattern (Figure 9).

A second pattern typical of those constituents that are relatively insoluble shows a constant low concentration in the leachate through the test period. Lead, manganese, and chromium are good examples of this type of leaching (Figure 10). This pattern of leaching may be modified by changes in any factor which modifies the solubility of the constituents. In several cases the initial leachate samples show elevated levels of the constituent before a constant concentration appeared. This pattern is illustrated by zinc in untreated wastes (Figure 11). Obviously, for those constituents with low solubility the total fraction leached during the test period was low compared with the total fraction leached for the more soluble constituents.

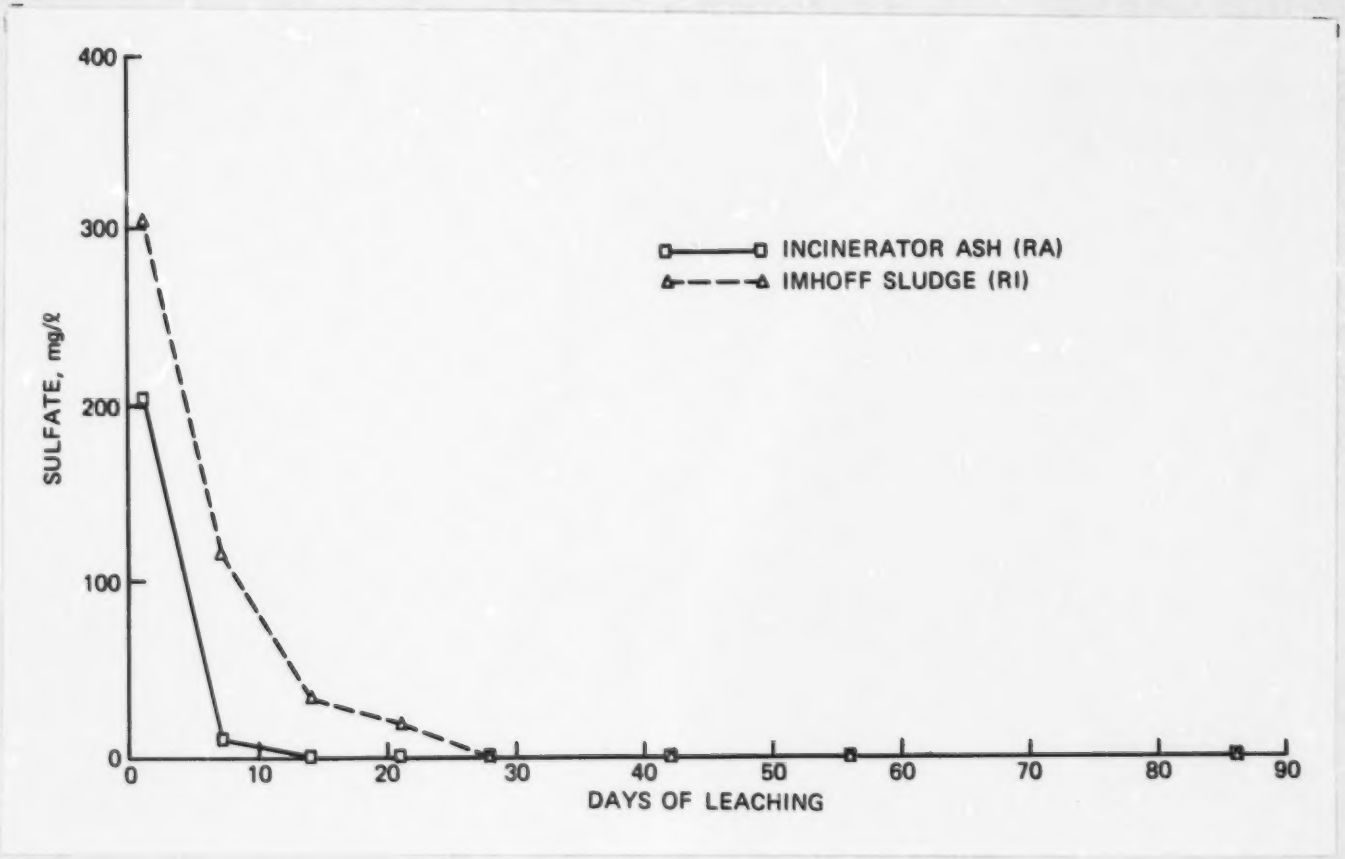

Figure 9. Concentration of sulfate leached from untreated sludges.

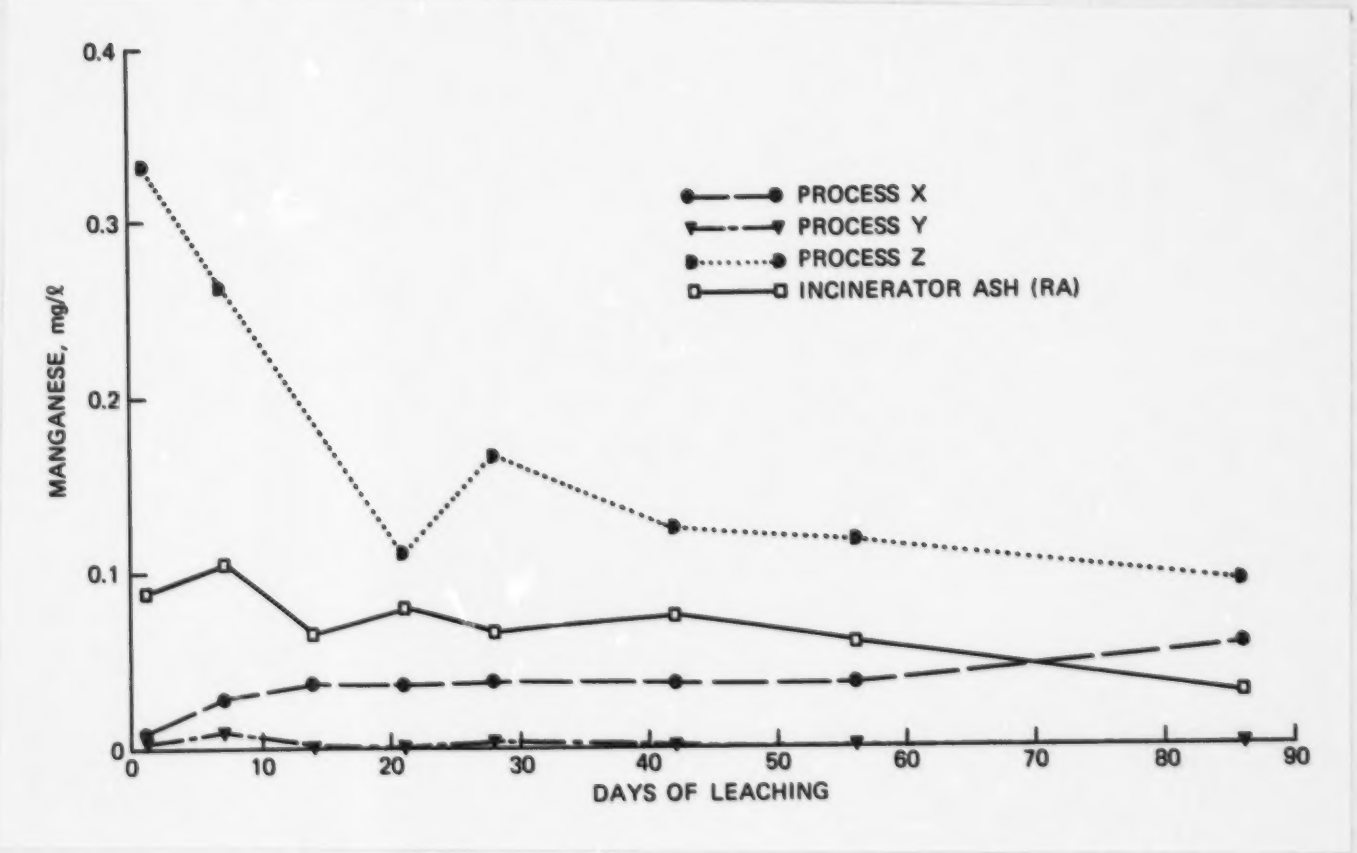

Figure 10. Concentration of manganese in leachate from treated and untreated incinerator ash.

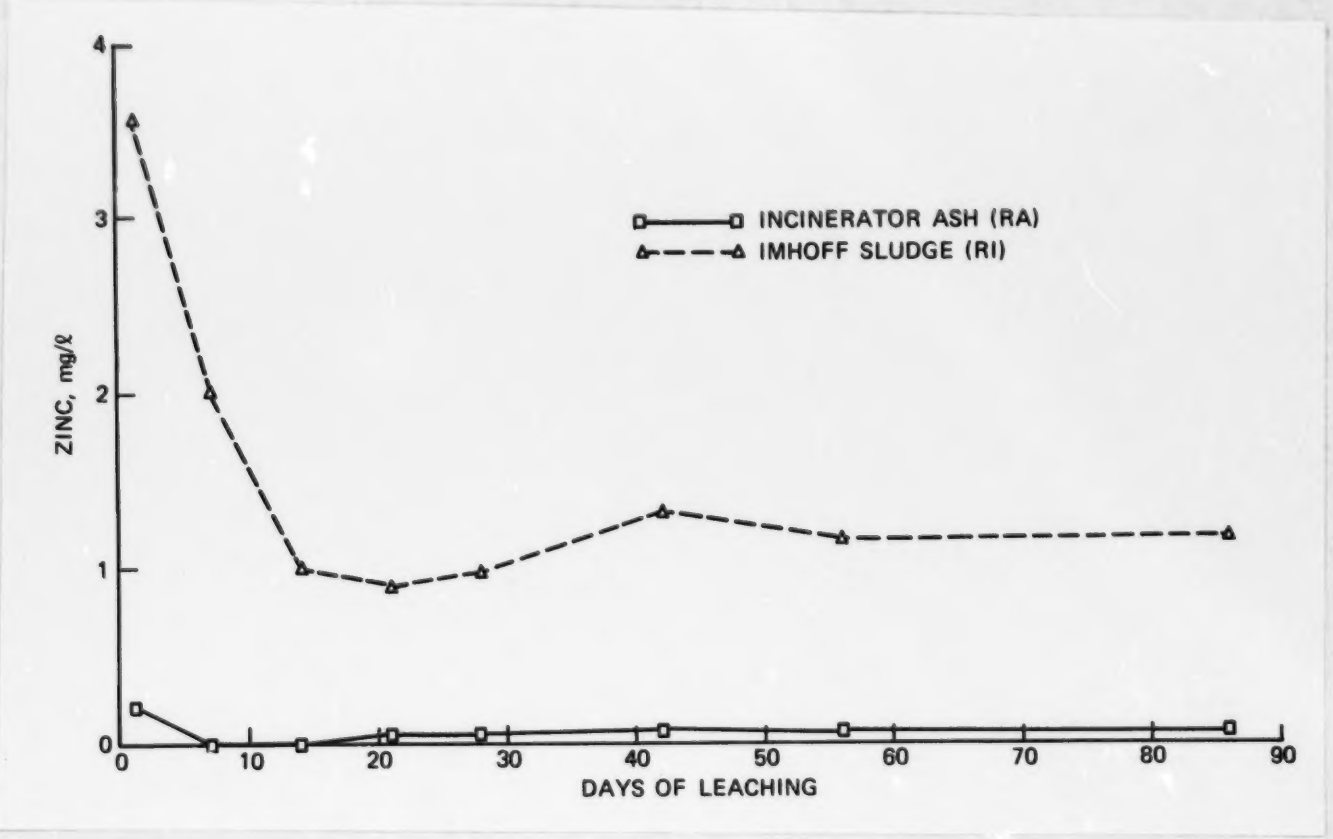

Figure 11. Concentration of zinc in leachate from untreated sludges.

For some compounds in the waste, low concentrations of the constituent are found in initial samples but higher levels appear in later samples (e.g., manganese for Process X leachates, Figure 8). This type of leaching pattern might be explained by such factors as common ion effects, changes in pH of the leach liquid, or by ion exchange phenomena. The pH of the leachate became lower (more acidic) in all vessels during the test period (Figures 12 and 13). This is probably due to the leaching of alkaline components by the acidic leaching liquid which lowered the buffering capacity in the waste.

Most of the leach constituents followed the first or second pattern in that larger amounts were leached in the first leaching intervals. Conductivity tended to follow a pattern showing high conductivities in the earlier leachate (Figures 14 and 15). Those treatments judged to be most effective at overall chemical stabilization are those in which the rate of total leaching as indicated by conductivity is lower compared with the untreated sludges.

The leaching solution was changed and measurements for pH and conductivity were made daily only during the work week (Monday through Friday). Consequently, leaching constituents increased in concentration in the leachate over the weekends due to the longer period of contact. The accumulated leachate constituents were reflected in high conductivity values on the first day of each week of testing (Figure 16). The pH values also showed a weekly cycle as the acidic leaching medium in the leach vessel had a longer time to react with the waste during the weekend. This cycle continued throughout the testing period. For this reason the pH and conductivity data were treated by using weekly averages of the values. This weekly variation did not interfere with the leaching patterns noted above.

Constituent Loss from Untreated Imhoff Sludge

An average of 121.2 grams of untreated sludge was compacted and loaded into the leach vessel thimble. This wet weight represented 69.9 grams of dry sludge solids. The total amount of each element leached, the amount leached on the first day, and the amount leached on the last day are given in Table 13. Leachate from untreated Imhoff sludge showed no concentrations of beryllium or selenium above detection limits. Arsenic was only observed at detectable levels toward the end of the leaching time, i.e., days 56 and 86. Concentrations of lead and chromium remained low in the leachate, but were present in a consistent amount throughout the study. Cadmium, copper, manganese, and zinc were present initially in relatively high concentrations then dropped to a constant low level. Iron did not appear in detectable concentrations in leachate for the first two weeks of the test, then moderate amounts were observed in the leachate for the next month. The highest concentration of iron appeared in leachate collected on the last test day. The increasing iron concentration is probably a function of decreasing pH of the leachate. Very soluble anions (sulfate and chloride) showed high concentrations in the initial days of the study, but the amounts rapidly decreased. Total organic carbon showed a pattern similar to that observed for sulfate or chloride.

The pH of the leachate from untreated Imhoff sludge decreased during the 13-week testing period (Figure 10 and Table 14). The pH on day 1 was 5.4 while the pH on day 86 was 4.4. The total amount of material in solution in

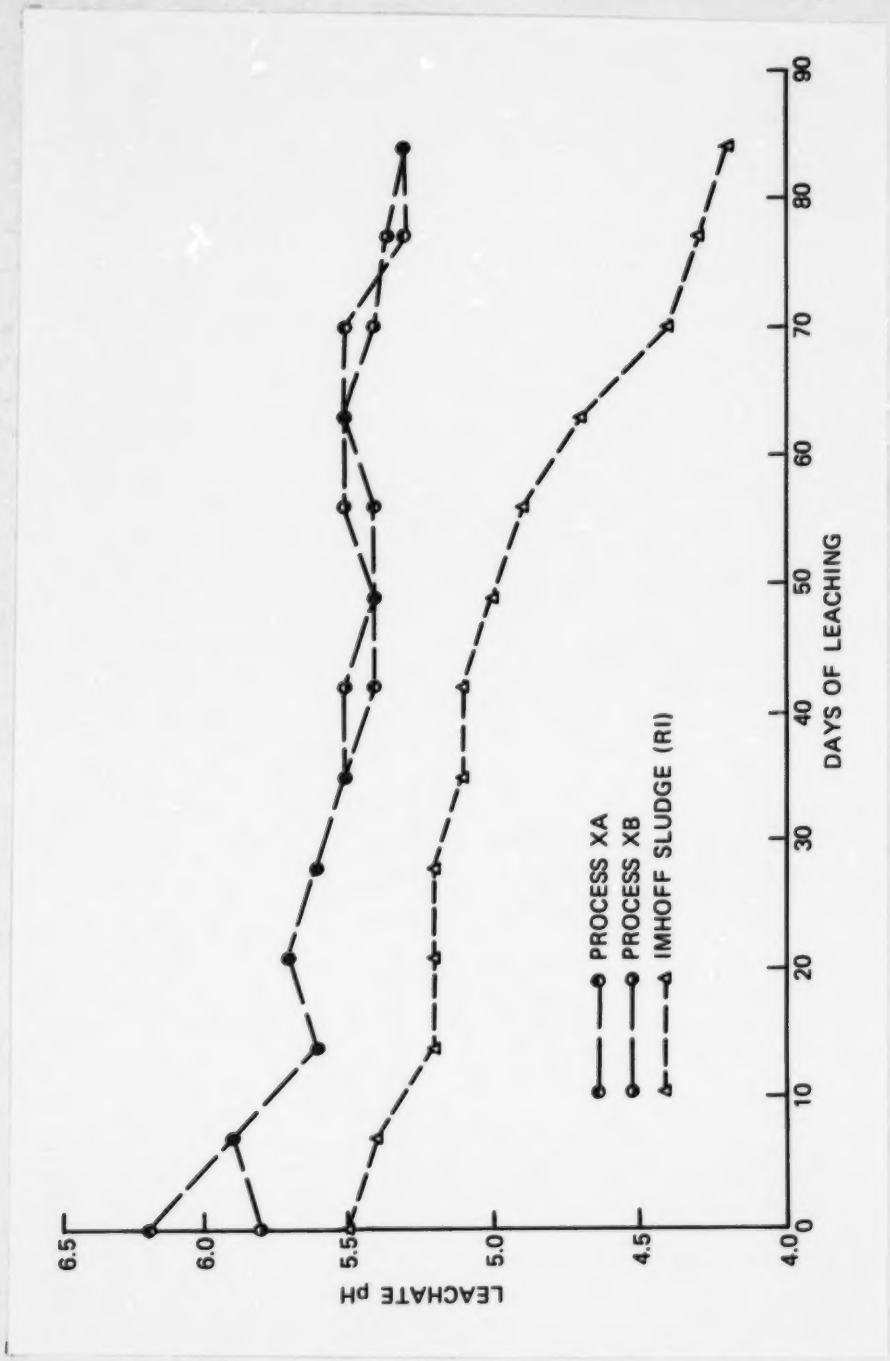

Figure 12. Mean weekly pH values of Imhoff sludge leachate (treated and untreated).

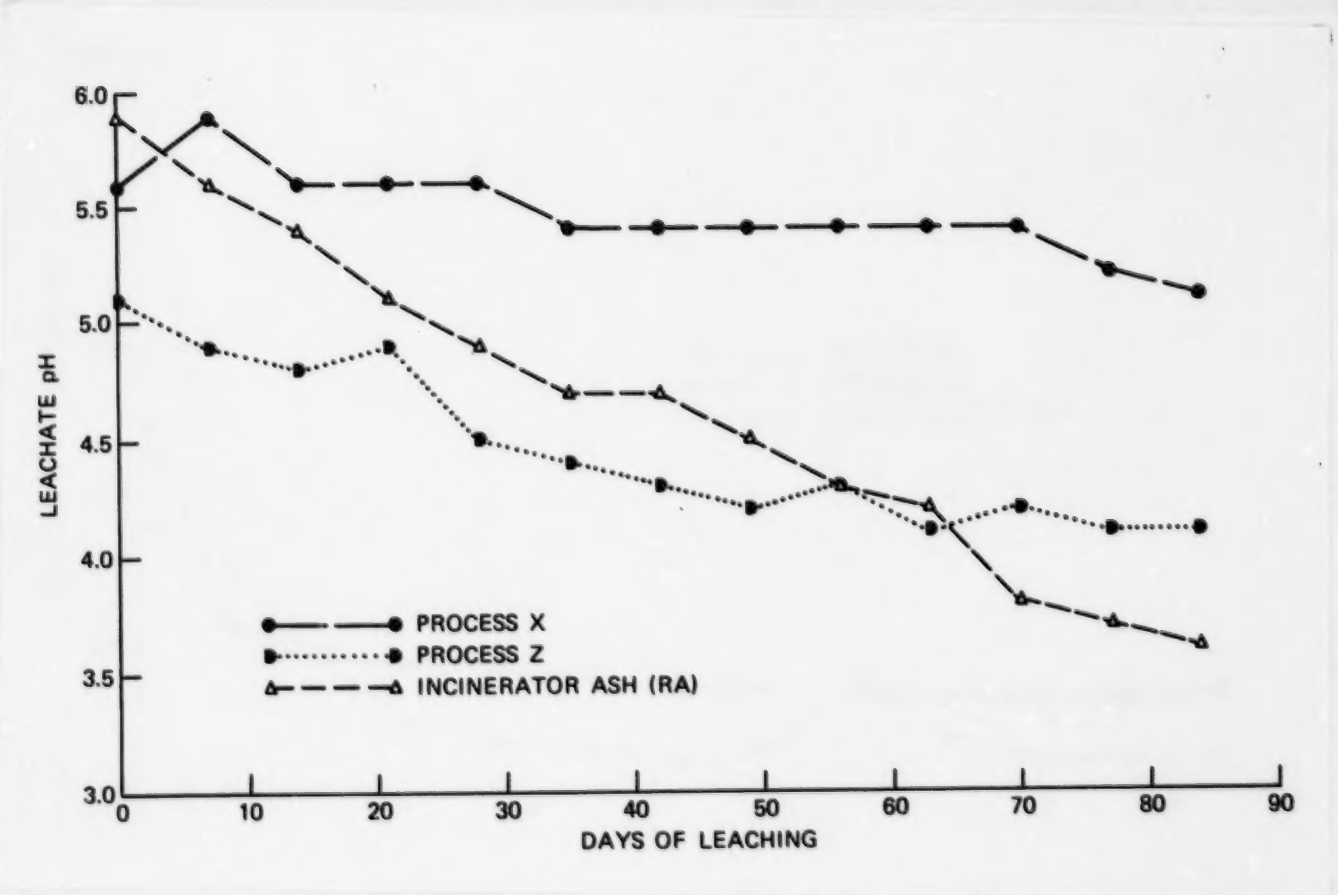

Figure 13. Mean weekly pH values of leachate from incinerator ash sludges (treated and untreated).

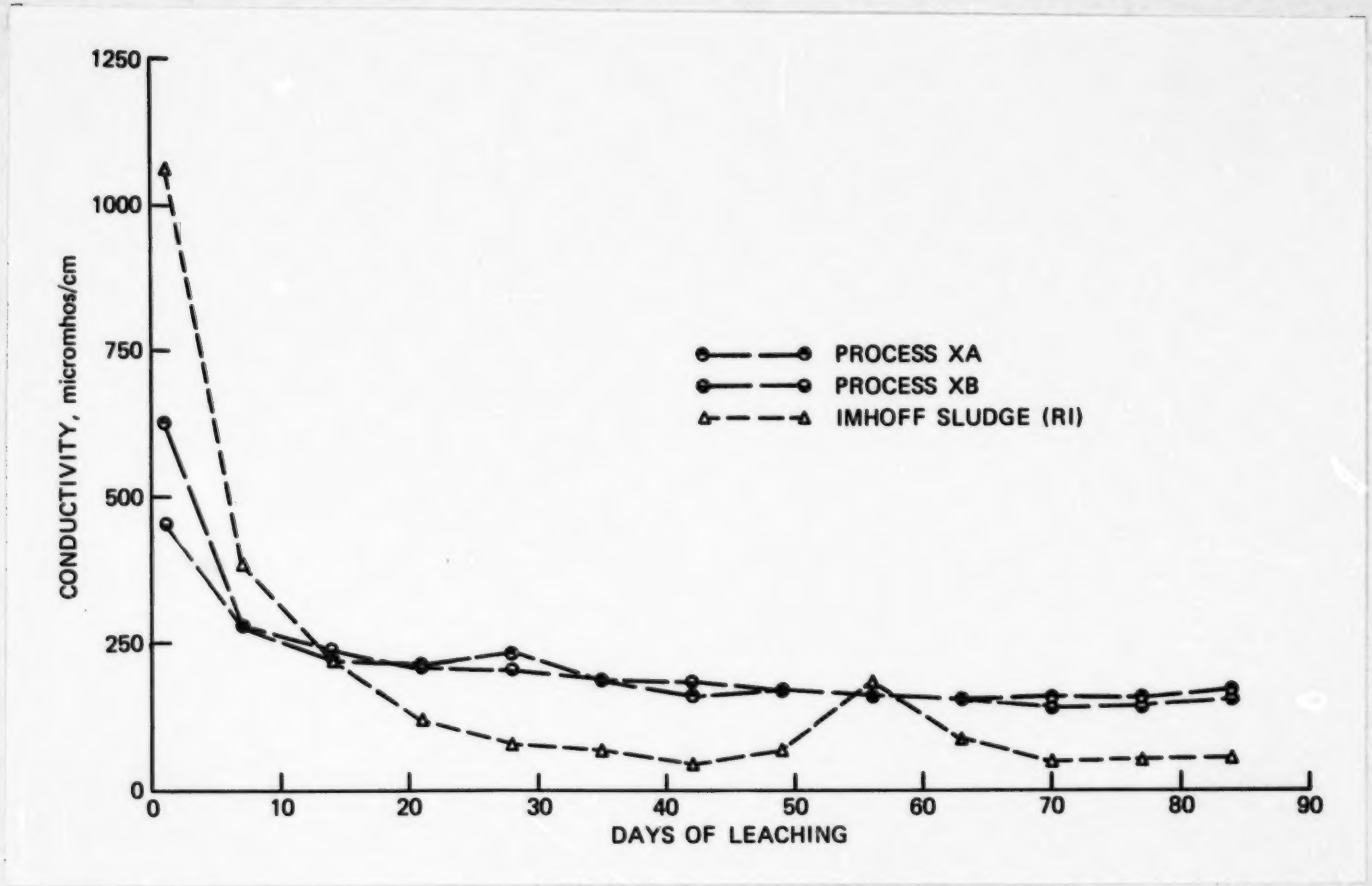

Figure 14. Mean weekly conductivity of leachate from Imhoff sludges (treated and untreated).

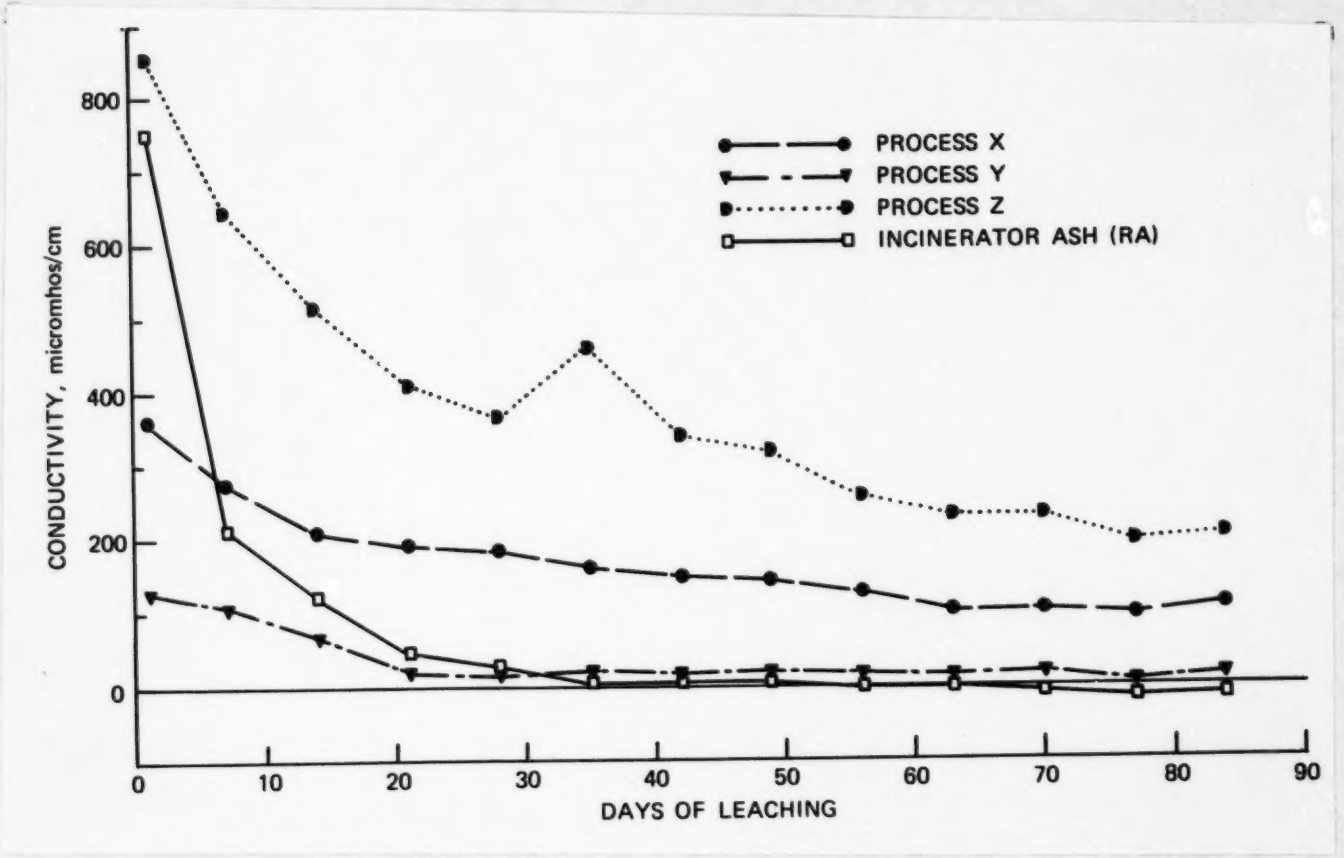

Figure 15. Mean weekly conductivity of leachate from incinerator ash sludges (treated and untreated). Negative values are due to background correction.

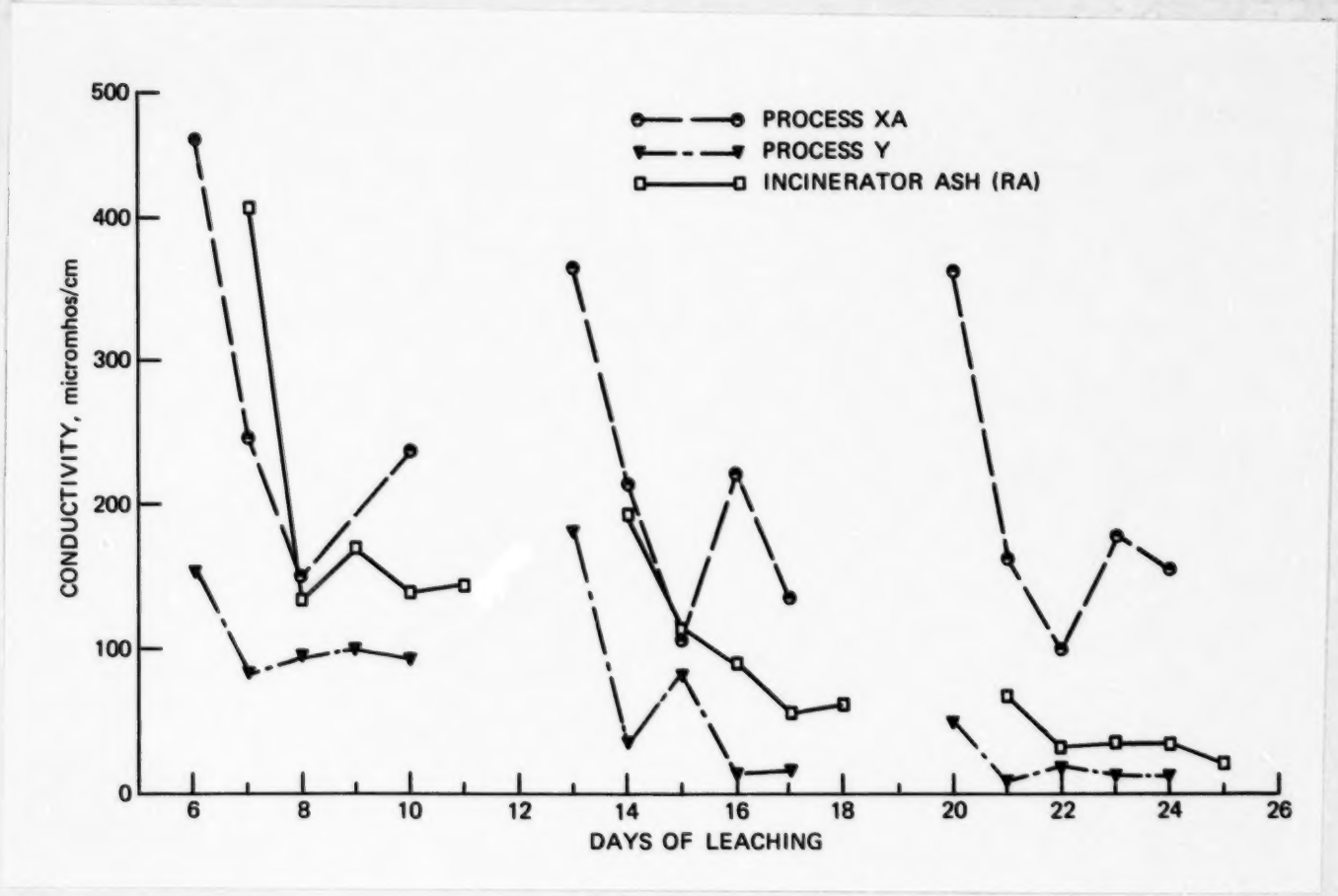

Figure 16. Daily average conductivity values for selected sludges for days 6 through 24.

TABLE 13. COMPOSITION OF LEACHATE FROM UNTREATED IMHOFF SLUDGE LEACHING TEST

Constituent	Average amount in sample (mg)	Amount leached (mg)		
		Total*	Day 1	Day 86
As	1.22	0.742	B	0.011
Be	†	B	B	B
Cd	14.8	3.30	0.113	0.049
Cr	214.2	0.566	0.005	0.016
Cu	95.6	3.86	0.142	0.035
Fe	158	48.4	B	1.30
Pb	79.0	0.238	0.002	0.009
Mn	19.7	11.5	0.642	0.077
Se	0.18	B	B	B
Zn	289	120	3.57	1.17
SO_4	1310	2680	305	B
Cl	23.3	130	28	B
TOC	8320	199	30.7	N

* Total mg of constituent in all leachates collected.

† B = below detection limits; N = no data.

NOTE: Each value is mean of three replicates. Values for Day 1 and Day 86 are in ppm as sample size = 1 liter.

TABLE 14. AVERAGE WEEKLY pH OF LEACHATE FROM IMHOFF SLUDGES (TREATED AND UNTREATED)

Midpoint day	Untreated Imhoff sludge (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
1	5.5*	6.1	5.8
7	5.4	5.9	5.9
14	5.2	5.6	5.6
21	5.2	5.7	5.7
28	5.2	5.6	5.6
35	5.1	5.5	5.5
42	5.1	5.4	5.5
49	5.0	5.4	5.4
56	4.9	5.4	5.5
63	5.7	5.5	5.5
70	4.4	5.5	5.4
77	4.3	5.3	5.3
84	4.2	5.3	5.3

* Each value is the mean of 3 replicates and 5 sampling days. All values are in standard pH units.

the leachate as indicated by conductivity was at a maximum during the first week (Figure 12 and Table 15) and rapidly fell to one-third the maximum value during the second week. After 4 weeks, the low levels of dissolved materials are shown by the low levels of the conductivity values.

Constituent Loss from Untreated Incinerator Ash

An average of 67.4 grams of untreated ash was loaded into the leach vessel thimble. This wet weight represented an average of 52.0 grams of dry solids. The total amount of each constituent leached, the amount leached on day 1, and the amount leached on day 86 are given in Table 16. The leachate from untreated incinerator ash contained no detectable selenium, beryllium, or iron during the test period. Levels of arsenic were low and, with one exception, appeared in detectable concentrations only after day 56. Zinc followed a similar pattern but detectable concentrations appeared earlier in the leaching sequence (day 21). Compared with untreated Imhoff sludge, levels of cadmium and copper were low; however, both metals were relatively constant in amount in the leachate from untreated ash. The levels of chromium and lead were higher in the ash than in the Imhoff sludge; both metals leached initially in large amounts reaching an equilibrium concentration near the analytical

TABLE 15. AVERAGE WEEKLY CONDUCTIVITY OF LEACHATE FROM IMHOFF SLUDGES (TREATED AND UNTREATED)

Midpoint day	Untreated Imhoff sludge (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
1	1068*	631	521
7	383	278	276
14	220	219	233
21	118	208	209
28	77	208	203
35	67	182	183
42	40	157	177
49	65	167	166
56	182	155	154
63	84	147	149
70	39	153	136
77	50	151	138
84	49	165	150

* Each value is the mean of 3 replicates and 5 sampling days. All values are in μmhos/cm.

TABLE 16. COMPOSITION OF LEACHATE FROM UNTREATED INCINERATOR ASH LEACHATE TEST

Constituent	Average amount in samples (mg)	Amount leached (mg)		
		Total*	Day 1	Day 86
As	0.695	0.472	0.01	0.0115
Be	B†	B	B	B
Cd	0.118	0.046	0.0006	0.006
Cr	29.4	0.336	0.056	0.002
Cu	39.0	2.77	0.054	0.045
Fe	874	B	B	B
Pb	60.6	0.325	0.003	0.009
Mn	40.7	5.61	0.089	0.029
Se	0.01	B	B	B
Zn	36.7	4.48	0.221	0.058
SO_4	323	1050	205	B
Cl	23.7	102	20.3	B
TOC	88.5	70.6	11.5	N

* Total mg of constituent in all leachates collected.

† B = below detection limits; N = no data.

NOTE: Each value is mean of 3 replicates. Values for Day 1 and Day 84 are in mg/l since sample = 1 liter.

detection limit by day 21 of the testing. Manganese, higher in concentration in the ash than in the Imhoff sludge, showed a constant concentration in the leach liquid. The anions, sulfate, and chloride and total organic carbon were present in lower amount in the ash than in the Imhoff sludge. They were not detected in the leachate after day 7.

The pH of the leachate from untreated incinerator ash became significantly lower during the 13-week testing period (Figure 11 and Table 17 show pH 5.9 on day 1 and pH 3.6 on day 84). Conductivity readings (Figure 13 and Table 18) indicate that all significant leaching occurred during the first five weeks of the study. After 6 weeks the conductivity readings were at background levels. Most of the material leached from the ash was removed during the first week of the test.

Constituent Loss from Treated Waste Samples

Several different data presentations and statistical analyses were prepared in evaluating the leaching data. The accumulated mass of each

TABLE 7. AVERAGE WEEKLY pH OF LEACHATE FROM INCINERATOR ASH (TREATED AND UNTREATED)

Midpoint day	Untreated incinerator ash (RA)	Process X (X)	Process Z* (Z)
1	5.9**	5.6	5.1
7	5.6	5.9	4.9
14	5.4	5.6	4.8
21	5.1	5.6	4.9
28	5.0	5.6	4.5
35	4.7	5.4	4.4
42	4.7	5.4	4.2
49	4.5	5.4	4.2
56	4.3	5.4	4.3
63	4.2	5.4	4.1
70	3.8	5.4	4.2
77	3.7	5.2	4.1
84	3.6	5.1	4.1

* Data from Process Y samples are not available due to an equipment malfunction.

** Each value is mean of 3 replicates and 5 sampling days. All values are in standard pH units.

TABLE 18. AVERAGE WEEKLY CONDUCTIVITY OF LEACHATE FROM INCINERATOR ASH (TREATED AND UNTREATED)

Midpoint day	Untreated incinerator ash (RA)	Process X (X)	Process Y (Y)	Process Z (Z)
1	757*	360	98	858
7	212	273	105	647
14	120	208	66	515
21	46	192	20	410
28	27	183	14	365
35	7	158	21	460
42	5	145	13	337
49	7	140	17	316
56	3	124	13	255
63	LTB (-4)**	98	12	229
70	LTB (-11)	100	15	230
77	LTB (-19)	91	3	193
84	LTB (-14)	104	10	202

* Each value is the mean of 3 replicates and 5 sampling days. All values are in μmhos/cm.

** LTB = conductivity less than that of blank.

constituent leached was determined by summing daily leaching losses. The accumulated mass of each chemical constituent leached in each treatment procedure and replicate vessel was tested for significant variation between the replications and treatments using a balanced design, analysis of variance (AOV). At no time was the variability seen within the replications significant at the 0.05 probability level. Treatment was seen as a significant source of variation in much of the data; consequently, the data were submitted to a Duncan Multiple Range test to determine significant differences between the means of the mass of each constituent leached from different treatment processes used to treat each waste type (Tables 19 and 20).

Since the treatment processes changed the chemical compositions of the sludges either through dilution of existing constituents or the addition of increased amounts of constituents via the treatment reagents, the total mass of each constituent leached was divided by the amount of each constituent originally in each waste sample to determine a total fraction of each constituent leached. These derived data were likewise submitted to the statistical analyses using AOV as described above (Tables 21 and 22). These results form the basis of discussion of the leach test results.

TABLE 19. DUNCAN'S RANGE TEST OF SIGNIFICANT DIFFERENCE IN THE MEAN TOTAL MASS OF CONSTITUENTS LEACHED FROM IMHOFF SLUDGES

Parameter	Compared to untreated		XA compared to XB
	XA	XB	
As	SL*	SL	NS
Cd	SL	SL	NS
Cr	NS	SH	SL
Cu	NS	SH	SL
Fe	SL	NS	NS
Pb	NS	NS	NS
Mn	SL	SL	SL
Se	†	†	SH
Zn	SL	SL	NS
SO_4	SL	SL	SL
Cl	SL	SL	NS
TOC	NS	SH	SL

* SL = means significantly lower and SH = significantly higher at the 0.05 probability level. NS = means not significantly different.

† Insufficient data for calculation.

TABLE 20. DUNCAN'S TEST OF SIGNIFICANT DIFFERENCES IN THE MEAN TOTAL MASS OF CONSTITUENTS LEACHED FROM INCINERATOR ASH

Parameter	Compared to untreated			X compared to Y	X compared to Z	Y compared to Z
	X	Y	Z			
As	†	NS*	SH	†	†	SL
Cd	NS	SL	SH	SH	SL	SL
Cr	SH	SL	SL	SH	SH	NS
Cu	SL	SL	NS	NS	SL	SL
Fe	†	†	†	†	†	†
Pb	SL	SL	SH	NS	SL	SL
Mn	SL	SL	SH	SH	SL	SL
Se	†	†	†	†	†	†
Zn	†	†	†	†	†	†
SO_4	SL	SL	SH	SH	SL	SL
Cl	SL	†	†	†	†	†
TOC	NS	NS	NS	NS	NS	NS

* SL = means significantly lower and SH = significantly higher at the 0.05 probability level. NS = means not significantly different.

† Insufficient data for calculation.

TABLE 21. DUNCAN'S TEST OF SIGNIFICANT DIFFERENCE IN THE MEAN TOTAL FRACTION OF CONSTITUENTS LEACHED FROM IMHOFF SLUDGES

Parameter	Compared to untreated		XA compared to XB
	XA	XB	
As	SL*	SL	NS
Cd	SL	SL	NS
Cr	SH	SH	SH
Cu	SH	SH	NS
Fe	SL	SL	NS
Pb	NS	NS	NS
Mn	SL	SL	NS
Se	†	†	SH
Zn	SL	SL	NS
SO_4	SL	SL	SL
Cl	SL	SL	NS
TOC	SH	SH	SL

* SL = means significantly lower and SH = significantly higher at the 0.05 probability level. NS = means not significantly different.

† Insufficient data for calculation.

TABLE 22. DUNCAN'S TEST OF SIGNIFICANT DIFFERENCE IN THE MEAN OF THE TOTAL FRACTION OF CONSTITUENTS LEACHED FROM INCINERATOR ASH

Parameter	Compared to untreated			X compared to Y	X compared to Z	Y compared to Z
	X	Y	Z			
As	†	NS*	SH	†	†	SL
Cd	NS	SL	SH	SH	SL	SL
Cr	SH	SL	SL	SH	SH	NS
Cu	SL	SL	SL	SH	SL	SL
Fe	†	†	†	†	†	†
Pb	SL	SL	SH	NS	SL	SL
Mn	SL	SL	SH	SH	SL	SL
Se	†	†	†	†	†	†
Zn	†	†	NS	†	†	†
SO_4	SL	SL	SL	NS	NS	NS
Cl	SL	†	†	†	†	†
TOC	SL	SL	SL	NS	NS	NS

* SL = means significantly lower and SH = significantly higher at 0.05 probability levels. NS = means not significantly different.

† Insufficient data for calculation.

Treated Imhoff Sludge Leaching Test Results

Two processes were used for solidification/stabilization of the Imhoff sludge. The effectiveness of solidification/stabilization can be estimated by changes in the rate and/or amount of constituents lost in the leach test when compared with that loss from the untreated sludge. Table 23 shows the total mass of selected constituents leached from Treatments XA and XB as compared with the untreated Imhoff sludge. The masses leached as presented in Table 23 are the means of three replications. In no case was the variability within the replicates significant. The total amount of treated sludge added to the leach thimble in the case of Process XA was 104.8 grams (for a dry solids content of 66.4 grams). For Process XB the wet weight was 105.2 grams (for a dry solids content of 65.6 grams). In wet and dry weight this compares favorably with the relative weights of the untreated sludge tested (121 grams of sludge or 69.9 grams of dry solids).

The chemical additives lowered the relative amounts of some metals and anions available to be leached (Table 2) through dilution. Consequently, a presentation of the data is made based upon the total fraction of each constituent leached as shown in Table 24. In this presentation the data are corrected for the differences in composition of each test sample by dividing

TABLE 23. TOTAL MASS OF CONSTITUENTS LEACHED FROM IMHOFF SLUDGES (TREATED AND UNTREATED)

Parameter	Untreated Imhoff sludge (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
As	0.742*	0.049	0.020
Cd	3.30	0.126	0.341
Cr	0.566	1.15	3.29
Cu	3.86	3.20	12.38
Fe	48.4	1.57	11.86
Pb	0.238	0.019	0.040
Mn	11.5	1.48	2.48
Se	BDL†	0.225	0.005
Zn	120	3.02	12.22
SO_4	2680	621	1440
Cl	130	28.3	65.0
TOC	199	190	654

* Mean of three replicates, all in mg.

† BDL = below detection limits in all leachate samples.

TABLE 24. TOTAL CONSTITUENT FRACTION LEACHED FROM IMHOFF SLUDGES (TREATED AND UNTREATED)

Parameter	Untreated Imhoff sludge (RI)	Process X Treatment A (XA)	Process X Treatment B (XB)
As	0.610*	0.080	0.029
Cd	0.222	0.072	0.059
Cr	0.0026	0.044	0.038
Cu	0.0405	0.283	0.313
Fe	0.386	0.002	0.011
Pb	0.003	0.002	0.001
Mn	0.581	0.224	0.210
Se	BDL†	13.3	0.147
Zn	0.416	0.079	0.103
SO_4	2.04	0.481	1.16
Cl	5.58	1.63	1.72
TOC	0.024	0.071	0.162

* Mean of three replicates.

† BDL = below detection limits in all leachate samples.

the mass leached by the mass available in the vessel to be leached. Each treatment is compared to the fraction leached from the untreated sludge. The fraction leached is the mean of three replicates. In no case is the variability within the replicates significant.

Treatment XA--

Treatment XA appeared to lower the leaching of arsenic, cadmium, iron, manganese, zinc, sulfate, and chloride when compared to the untreated sludge. A balanced design AOV showed that, in all the above variables, the total fraction leached (i.e., total mass leached/total mass available for leaching) was significantly lower in the leachate from treated sludges than in the leachate from the untreated sludges (Tables 19 and 21). In the case of two heavy metals, chromium and copper, and for total organic carbon, the total fraction leached was significantly higher in the treated sludges than in the untreated sludge (Table 21). These three constituents showed no significant differences when compared on the basis of total mass leached (Table 19). The statistically lower total mass leached arises from the fact that the dilution during treatment lowered the amount available for leaching. The actual rate of leaching was not increased by the treatment.

In the case of selenium, no leaching was observed in the untreated sludge, but selenium was detected in the leachate from the treated sludge.

The actual amount leached in both cases may have been similar, however, since the selenium concentrations measured were near the detection limit. The leaching rate of lead remained unchanged in treated sludge as compared to untreated sludge.

The final pH of the leaching liquor became only slightly more acidic during the testing period (Figure 12 and Table 14, pH was 6.1 on day 1 and pH was 5.7 on day 86). Treatment XA significantly buffered the treated materials as compared with the untreated sludge. As with other samples, the leachate conductivity was initially high (Figure 14 and Table 15, 630 μmhos per cm). The conductivity dropped to a value approximately one-half the initial value (275 μmhos per cm) by the second week and thereafter decreased only slightly during the remainder of the testing period (185 μmhos per cm, day 86). Moderate levels of ionic material continued to be leached over the length of the experiment. Leaching rates in general were significantly lower, and thus the treated materials exhibit improved containment properties.

Treatment XB--

The composition of leachate from sludges treated by Process XB paralleled that of leachate from Process XA treated wastes. The leaching of arsenic, cadmium, iron, manganese, zinc, sulfate, and chloride was significantly lower in the treated sludge as compared to the untreated sludge. Significant differences were observed in both the total fraction leached and in the total mass leached. As with Treatment XA the total fraction leached for chromium, copper, and total organic copper was significantly higher in the treated sludge as compared with the untreated. However, in contrast to the case of Treatment XA, the total mass leached for these parameters was also significantly higher. Some aspects of the solidification process increased the solubility of chromium, copper, and total organic carbon, thereby increasing the leaching rate rather than improving the containment of these constituents. Slightly increased leaching was observed in the case of selenium; no leaching was observed for selenium in the untreated sludge. It should be noted, however, that the levels of selenium observed in leachate from sludges treated by Process XB were at the lower detection limit for selenium. No significant change was observed in the leaching of lead.

The pH of the leaching liquid did not change significantly during the testing procedure (Figure 12 and Table 14, pH 5.8 on day 1 and pH 5.7 on day 86). The conductivity was higher on day 1, 525 μmhos per cm (Figure 14, Table 15), then fell to a value about one-half the maximum by the second week (275 μmhos per cm), and then decreased slightly during the remaining weeks (165 μmhos per cm, day 86). As is the case of Treatment XA, slowed leaching was observed when the results of pH and conductivity readings from sludges treated by Process XB were compared with readings from the untreated sludges.

Comparison of Treatment XA with XB--

When Treatment XA is compared with Treatment XB, several differences are observed. Firstly, it appears that Treatment XB increased the loss of the metals, chromium and copper, and increased leaching of the total organic carbon component where this was not observed with Process XA. The total fraction leached from sludges treated by Process XB was lower for chromium and selenium

than for the sludges treated by Process XA. Copper showed no significant difference; however, the total amount leached for chromium, copper, manganese, sulfate, and total organic carbon was significantly higher for Treatment XB than for Treatment XA. Only in the case of selenium was Treatment XA higher in leached mass and fraction leached than Treatment XB. A summary of the statistical analyses of the total mass leached and the overall fraction leached is given in Tables 19 and 21.

The change in the pH of the leachate from sludge treated by Process XA was greater than the pH change in the leachate from sludges treated by Process XB; however, both treatment processes produced leachate of the same final pH value. The initial values for leachate from Process XA sludges was somewhat higher perhaps due to increased amounts of lime added (Figure 12 and Table 14, 6.1 for XA, 5.8 for XB). The conductivity measured in leachate from the sludges treated by Process XA was also initially higher (Figure 14 and Table 15, 630 μmhos per cm for XA, 525 μmhos per cm for XB); however, between week 2 and week 14 the total decrease in conductivity for leachate from sludge treated by Process XA was about 100 μmhos per cm. This compares well with the change observed in conductivity for leachate from sludges treated by Process XB (100 μmhos per cm).

On the basis of this study, Process XA appears to be the better at reducing the concentration of the particular constituents measured both in total mass and total fraction present when Imhoff sludge is the processed waste.

Treated Incinerator Ash Leaching Test Results

Three treatment processes were tested with the incinerator ash to determine their ability to contain potential pollutants. The effectiveness of chemical stabilization can be judged by the changes in rate and amount of constituents leached from the treated products as compared with the untreated waste. Table 25 shows the total mass of selected metals, anions, and total organic carbon leached from sludges treated by Processes X, Y, and Z as compared with the untreated sludge. The mass leached is the mean of three replicates. In no case was the variability within the replicate samples significant.

The total amount of treated sludge added to the leach vessel thimble produced by Process X was 106 grams (dry solids, 62.2 grams). Samples for Process Y weighed 134 grams (dry solids, 87.4 grams). Samples for Process Z weighed 133 grams (dry solids, 67.9 grams). This compares to 67.3 grams (dry solids, 52.0 grams) of wet in the untreated ash vessels. The concentrations of constituents in the treated incinerator ash products differed from the concentration of components of the untreated product in several aspects (Table 3). Untreated ash was low in total organic carbon. The amount of total organic carbon increased in all treatments by 50% to 100%. Process Z-stabilized products showed greatly increased levels of sulfate. Other constituents of the waste were lower in final amounts due to the dilution of materials used in treatment, except for increased levels of chromium, copper, iron, manganese, and zinc in the treated solid produced by Process Y.

TABLE 25. TOTAL MASS OF CONSTITUENTS LEACHED FROM INCINERATOR ASH (TREATED AND UNTREATED)

Parameter	Untreated incinerator ash (RA)	Process X (X)	Process Y (Y)	Process Z (Z)
As	0.472*	BDL†	0.511	2.19
Cd	0.046	0.044	0.0185	0.083
Cr	0.336	0.637	0.0627	0.038
Cu	2.77	0.389	0.156	1.20
Fe	BDL	BDL	BDL	8.00
Pb	0.325	0.042	0.074	0.625
Mn	5.61	3.56	0.10	11.7
Se	BDL	BDL	BDL	BDL
Zn	4.48	BDL	BDL	1.38
SO_4	1050	656	111.5	8970
Cl	102	55.0	BDL	BDL
TOC	70.6	30.8	30.2	42.2

* Mean of three replicates; all in mg.

† BDL = below detection limits in all leachate samples.

The total fraction of each constituent lost during the leaching test is presented in Table 26. The fraction leached, a correction for changes in chemical composition during treatment, is generated by dividing the total mass leached by the total amount of the constituent available for leaching in the test sample. As in the preceding tables, leach loss from each treated sample is compared to the loss from the untreated waste for each of the selected variables. The fraction leached is the mean of three replicates. In no case was the variability within the replicate samples significant at the 0.05 probability level.

Treatment X--

Process X produced a treated product that showed a significant decrease in leaching loss of copper, lead, manganese, sulfate, chloride, and total organic carbon in the total fraction leached as compared with the untreated sample. Only in the case of chromium was the fraction leached from the treated ash significantly higher than for the untreated samples. In the case of cadmium there was no significant change in the fraction leached when leachate from Process X was compared with the leachate from the untreated sludge. Iron, selenium, arsenic, and zinc were below detection limits in all leachate samples from the treated sludge.

TABLE 26. TOTAL FRACTION LEACHED FROM INCINERATOR ASH (TREATED AND UNTREATED)

Parameter	Untreated incinerator ash (RA)	Process X (X)	Process Y (Y)	Process Z (Z)
As	0.680*	BDL†	0.464	0.351
Cd	0.393	0.522	0.087	0.821
Cr	0.011	0.032	0.002	0.0012
Cu	0.071	0.013	0.002	0.034
Fe	BDL	BDL	BDL	0.0085
Pb	0.0050	0.0090	0.0007	0.0144
Mn	0.138	0.110	0.0013	0.312
Se	BDL	BDL	BDL	BDL
Zn	0.122	BDL	BDL	0.0357
SO_4	3.25	1.23	0.245	0.554
Cl	4.29	3.35	BDL	BDL
TOC	0.797	0.142	0.119	0.243

* All values are the mean of three replicates.

† BDL = below detection limits in all leachate samples.

The pH of leachate from waste treated by Process X increased during the treatment period by 0.2 unit (Figure 13 and Table 17). This is in contrast to the leachate from untreated ash which decreased by over a full pH unit. The total leaching of materials from the treated sludge, as indicated by conductivity, was slowed significantly by the treatment process. The initial loss (week 1) as reflected by conductivity decreased consistently (Figure 15 and Table 18, 360 µmhos per cm, X; 757 µmhos per cm, untreated). Where conductivity in the leachate from untreated waste was at background level by week 6, leaching loss on day 84 for waste treated by Process X was at one-third the initial rate on day 84. The conductivity of leachate from treated waste was lower initially than conductivity of leachate from untreated waste and the conductivity of the leachate from the treated material decreased more slowly.

Treatment Y--

Process Y significantly lowers the leaching rates of cadmium, chromium, copper, lead, manganese, sulfate, and total organic carbon. These parameters were significantly lower in both the total mass leached and total fraction leached, indicating a true containment of the constituents. Samples treated by Process Y show increased amounts of several metals in the treated samples, but these constituents do not contribute significantly to the total mass leached in the test results. Only in the case of arsenic was there no significant difference in the rate of leaching when the treated sludge was

compared to the untreated controls. Iron, selenium, zinc, and chloride were below analytical detection limits in leachate from the treated sludge.

The conductivity of leachate from ash treated by Process Y was consistently low, indicating little material in solution. The maximum value obtained was 125 μmhos per cm on day 1 (Figure 15 and Table 18). This value is approximately one-eighth the conductivity measured for leachate from the untreated sludge on day 1. Data for pH for leachate from Process Y-treated ash were not available due to an equipment malfunction that was not detected until testing was complete.

Treatment Z--

Samples treated by Process Z show a significantly lower fraction leached for only four constituents, chromium, copper, sulfate, and total organic carbon, when the leachate from the treated samples is compared with the leachate from untreated samples. If, however, the increased amounts of these constituents due to processing are considered (total mass leached) only the difference in loss of chromium is significantly lower. In fact, samples treated by Process Z show greatly increased amounts of sulfate in the final treatment sludge due to the treatment procedure (240,000 mg/kg for Process Z, 6,200 mg/kg for the untreated); consequently, the mass leached was significantly higher for sulfate in the treated sludge. The amount of total organic carbon was approximately doubled in the treated ash but the mass leached shows no significant change. For these two variables, the total mass leached might be a more acceptable presentation of the data to be used for judging the effectiveness of Process Z in the chemical stabilization of the ash. The total fraction leached was significantly higher in the leachate from treated ash (Process Z) for arsenic, cadmium, lead, and manganese when composition of leachate was compared with the untreated samples. In the case of zinc there was no significant change in the mass leached or total fraction leached for this treatment process. Iron, selenium, and chloride were below detection limits in all leachate samples.

The pH of leachate from wastes treated by Process Z followed the same pattern of change in pH seen in the untreated incinerator ash. The leachate initially had a pH of 5.1 then became more acidic as testing progressed (Figure 13 and Table 17, pH 4.2 on day 86). The conductivity of the leachate from ash treated by Process Z was higher than that of the untreated material at all times, indicating an increased concentration of dissolved material in the leachate (Figure 15 and Table 18). The conductivity was 858 μmhos/cm on day 1 for treated, 757 μmhos/cm on day 1 for untreated, 202 μmhos/cm on day 86 for treated, and BDL on day 86 for untreated. These data indicate that for Process Z the leaching loss was not decreased in either rate or amount.

Comparison of Treatments X, Y, and Z--

When the three treatment processes used on the ash are compared it appears that Process Y is the most effective at retarding leaching losses. In almost every case tested the amount or fraction leached from ash samples treated by Process Y was lower than that observed with the untreated ash or any of the other treated ash samples. A single exception was for arsenic leached from samples treated by Process X, where arsenic was below detection limits. In the cases of cadmium, copper, and manganese leaching loss from

samples treated by Process Y was markedly lower than from materials produced by the other treatment procedures.

Process Z is the least effective in slowing the leaching process. In four variables (arsenic, cadmium, lead, and manganese) the fraction leached from the treated ash was significantly higher than for the other treated wastes or from the untreated samples. If the large amount of sulfate added in processing is considered, this fifth variable may be included in the above list. For no constituent was Process Z clearly the best treatment of the three considered for slowing leaching loss. The leaching of chromium from samples treated by Process Z was lower than from samples treated by Process X but this is the only constituent that showed lower leaching rates when leachate from samples treated by Process Z was compared with the leaching from any of the other treated sludges.

Process X occupies the middle ranking. Other than for arsenic, Process X was less effective at slowing leaching loss than was Process Y. Samples treated by Process X, however, showed significantly lower leaching rates for cadmium, copper, lead, and manganese than did samples treated by Process Z. Only in the case of chromium was the leaching loss from sludges treated by Process X in excess of the leaching loss from the other samples.

Of the three treatment processes used for stabilization of incinerator ash, Process X was able to maintain a high pH in the leachate. The pH change of the leachate from sludges resulting from treatment by Process Z paralleled that of the untreated wastes (becoming acidic). No pH data are available for Process Y. While all three processes appeared to reduce the initial conductivity of the leachate and retard leach losses, Process Y was most effective. Process Z was least effective. In fact, total leaching loss appears to have been increased by Process Z treatment. Process X was intermediate in its effect on total leaching loss as measured by conductivity.

A summary of the statistical analyses of the total mass leached and the overall fraction leached for all incinerator ash specimens is given in Tables 20 and 22.

SECTION 6

DISCUSSION

The disposal of sewage treatment wastes or POTW wastes and sludges presents an environmental problem in their loss of noxious and/or toxic constituents to contacting water. This study examines the effectiveness of three different chemical solidification/stabilization processes in limiting the contaminant loss. Treatment effectiveness is assessed using a static leaching procedure. Physical characteristics and durability of the treated products are also assessed.

To be successful in treating POTW wastes, solidification/stabilization processes must limit or retard the loss of waste constituents. This can be achieved by isolating the waste materials and/or by creating a chemical environment in the wastes which reduces the solubility and reactivity of the constituents that must be contained. Isolation of the waste can also be brought about either by encapsulating the waste within some inert material, or by reducing the effective surface area of the waste by producing an impermeable monolith.

For those treatment processes which rely upon solidification to isolate the waste, the effectiveness of the solidification process can be a function of selected physical properties of the final product such as permeability, density, void space, and durability. Permeability would indicate the ease of movement of water, and thus any soluble materials, through the processed waste, and therefore the rate of movement of materials out of the internal portions of the treated waste. Increased density and lowered void space both would generally imply lower permeabilities and internal diffusion rates. Durability is important in estimating the long-term effectiveness of the solidification processes in isolating the wastes.

Chemical attributes which should have a predictive value in estimating containment effectiveness include the ability of the waste material to maintain an optimum pH (usually an alkaline condition) at leachate/waste interfaces, and the lowered solubility and/or reactivity of any new compounds produced in the treatment processes. Ultimately the true test of the chemical binding or containment is a well-designed leach test.

The three treatment processes included in this study produced very different treated waste products. Only those of Process Y were truly solidified into a monolith with good structural integrity. This solidified product gave the best containment of sludge constituents of any of the treatment processes, releasing lower amounts of the majority of metals and anions than the untreated sludge under the stated test conditions. Leachates from Process Y-treated ash

showed lower conductivities and caused less change in the leachate pH (indicating little interaction with the sample) than those from other treated specimens.

Process X produced a cured material which had the appearance of a hardened, clay soil which crumbled easily into small chunks. The samples produced from the Imhoff sludge by Process X were much softer, perhaps due to the higher level of organic materials they contained. Overall the specimens produced from by Process X from both POTW wastes lost smaller amounts of many constituents to the leaching medium than the respective untreated wastes. Leachates from these samples changed in pH more than any other treated or untreated samples indicating the strongly alkaline character of the treated waste. The conductivities of the leachate from these samples, however, were generally higher than those of the untreated wastes after two or three weeks of leaching. The long-term loss of dissolved materials which exceeded that of the raw sludges should be considered in any future evaluation procedures.

Process X contributed three different treated materials to the study and this forms the basis of comparison between the ease of containment of the two POTW wastes. Treatments XB of Imhoff sludge and X of incinerator ash were the most similar in relative amounts of dry sludge solids (50.4 and 52.6 kg respectively) and treatment reagents (32.7 and 22.2 kg respectively) and therefore give the best basis of comparison. Both treatments of both sludges had significantly lower masses leached than their respective untreated sludges for arsenic, cadmium, manganese, zinc, sulfate, and chloride; both were higher than their untreated counterparts for chromium, copper, and total organic carbon (see Tables 19 and 20). The only difference found between the two waste types was for iron for which a significantly lower fraction was leached from the treated Imhoff sludge compared to the untreated Imhoff sludge; but for which no significant difference was found between the treated and untreated incinerator ash. Both treated products also had similar physical properties. Even though the Imhoff sludge contained significant amounts of organic material and higher levels of heavy metals, the relative containment properties of the two sludges as measured after this treatment process were quite similar.

Two different levels of dry sludge solids and additives were used by Process X on the Imhoff sludge. Treatment XA contained 2.7 parts of treatment additives for each part of dry sludge (by weight) while Treatment XB had 0.65 parts of additive per part dry sludge solids (Table 4). This is a relative difference of over three times. Although both had leachate levels significantly lower than the untreated sludge leachates for arsenic, cadmium, manganese, zinc, sulfate, and chloride, Treatment XA lost significantly lower levels of chromium, copper, manganese, sulfate, and total organic carbon than the Treatment XB specimens (Table 19). The much higher relative additive level in the XA specimens did significantly increase the containment efficiency for these constituents. Selenium on the other hand appears to be added in the treatment process since none was detected in the untreated sludge leachate and Process XA leached significantly more than Process XB, exactly the reverse of those constituents listed above.

The treated product produced by Process Z remained wet and did not harden. When preliminary testing indicated that this was the case the vendor

was contacted and suggested that the freshly treated material be filtered to remove excess water and the moist filtrate air-dried. This procedure was followed on the final processing attempt; however, the end product remained wet and would not hold its shape.

Process Z-treated materials lost the largest proportion of their constituents in the leaching test. These leachates also had the most acidic pH values indicating a low buffering capacity or unneutralized acid in the processed samples. The addition of acidic reagents to the ash apparently brings many metals into solution. Also the level of sulfate in these leachates is extremely high and persistent and is apparently added in the treatment reagents (gypsum).

The largest proportion of dry sludge solids included in any of the treatment processes for which the actual formulations are known (not including Process Y) was about 20% of the weight of the final product (see Table 4). Therefore, at a minimum, 4 times as much waste (by weight) must be dealt with after processing with these methods as before. And about 60% of all treated products was added water which must be incorporated into the matrix. This 4:1 dilution of the waste must be taken into account when evaluating the cost effectiveness of these waste treatment processes. Process Y used only 10 to 25% of the weight of treatment reagents, and less than half the amount of water that was used by both other processes giving 3 to 10 times as much dry sludge solids in the end product. It also produced the best containment efficiency and most durable product. It did require that the treated waste be compacted to attain these results, but this should not be difficult under field conditions.

The use of selected solidification/stabilization technology on sewage treatment plant, Imhoff digester sludge, or incinerator ash is shown to decrease the loss of its constituents to contacting waters. The use of pozzolonic reagents with small amounts of water and post-mixing compaction appears to give the best results of those included in this study.

REFERENCES

American Society for Testing and Materials. 1973. Annual Book of ASTM Standards. Part II. Philadelphia, Pa. 717 pp.

Fields, T., Jr., and A. W. Lindsey. 1975. Landfill Disposal of Hazardous Wastes: A Review and Known Approaches. EPA-530/SW-165, U. S. Environmental Protection Agency. Cincinnati, Ohio. 36 pp.

Geraghty and Miller, Inc. 1978. Surface Impoundments and Their Effects on Groundwater Quality in the United States--A Preliminary Survey. EPA-570/9-78-004. U. S. Environmental Protection Agency. Washington, D. C. 275 pp.

Ham, R. K., M. A. Anderson, R. Stegmann, and R. Stanforth. 1979. Comparison of Three Waste Leaching Tests. EPA-600/2-79-071. U. S. Environmental Protection Agency. Cincinnati, Ohio. 234 pp.

International Atomic Energy Agency. 1971. Leach Testing of Immobilized Radioactive Waste Solids, A Proposal for a New Standard Method. In: Atomic Energy Review, E. D. Hespe, ed. Vol 9. pp 195-207.

Karafiath, L. L. and E. A. Nowatzki. 1978. Soil Mechanics for Off-Road Vehicle Engineering. Trans Tech Publications. 515 pp.

Lowenbach, W. 1978. Compilation and Evaluation of Leaching Test Methods. EPA-600/2-78-095. U. S. Environmental Protection Agency. Cincinnati, Ohio. 111 pp.

Lunt, R. R., et al. 1977. An Evaluation of the Disposal of Desulfurization Wastes in Mines and the Ocean, Initial Assessment. EPA-600/7-77-015. U. S. Environmental Protection Agency. Washington, D. C. 318 pp.

Malone, P. G., and N. R. Francingues. 1981. Treatment of Toxic and Hazardous Wastes Using Stabilization/Solidification Technologies. Presented at Great Plains Wastewater Design Conference. Omaha, Nebraska. 13 pp.

Malone, P. G., and L. W. Jones. 1979. Survey of Solidification/Stabilization Technology for Hazardous Industrial Wastes. EPA-600/2-79-056. U. S. Environmental Protection Agency. Cincinnati, Ohio. 48 pp.

Malone, P. G., L. W. Jones, and R. J. Larson. 1980. Guide to the Disposal of Chemically Stabilized and Solidified Wastes. SW-872. U. S. Environmental Protection Agency, Washington, D. C. 126 pp.

McClain, W. C., R. L. Bradshaw, and F. M. Emson. 1967. Disposal of High-level Solidified Wastes in Salt Mines. Disposal of Radioactive Wastes in the Ground. International Atomic Energy Agency. Vienna, Austria. pp 559-659.

Miller, D. W., F. A. DeLuca, and T. L. Tessier. 1974. Groundwater Contamination in the Northeast States. EPA-660/2-74-056. U. S. Environmental Protection Agency. Washington, D. C. 325 pp.

Page, A. L., and P. F. Pratt. 1975. Effects of Sewage Sludge or Effluent Application to Soil on the Movement of Nitrogen, Phosphorus, Soluble Salts and Trace Elements to Groundwater. Proceedings of the 1975 National Conference on Municipal Sludge Management and Disposal. Information Transfer Inc. Rockville, Md. pp 179-187.

Phung, T., L. Barker, D. Ross, and D. Barnes. 1978. Land Cultivation of Industrial Wastes and Municipal Solid Wastes, Vol I and II. EPA-600/2-78-140a and b, U. S. Environmental Protection Agency. Cincinnati, Ohio. 220 pp and 173 pp.

Robson, S. G. 1977. Groundwater Quality near a Sewage-Sludge Recycling Site and a Landfill near Denver, Colorado. U. S. Geological Survey, Water Resources Investigations 76-132, Washington, D. C. 137 pp.

U. S. Department of the Army. 1970. Laboratory Soils Testing. Engineer Manual. EM 1110-2-1906. U. S. Department of the Army. Washington, D. C. No pagination.

U. S. Environmental Protection Agency. 1976a. Proposed Revision of Ocean Dumping Regulations and Criteria. Federal Register 40CFR220-226.

U. S. Environmental Protection Agency. 1976b. Manual of Methods for Chemical Analysis of Water and Wastes. EPA-625/6-74-003a. U. S. Environmental Protection Agency. Cincinnati, Ohio. 298 pp.

U. S. Environmental Protection Agency. 1978. Sludge Treatment and Disposal, Vol 1, Sludge Treatment. EPA-625/4-78-012. U. S. Environmental Protection Agency. Cincinnati, Ohio. 140 pp.

U. S. Environmental Protection Agency. 1980a. Hazardous Waste Management System; Identification and Listing of Hazardous Wastes. Federal Register Part III. 45(98):33083-33133.

U. S. Environmental Protection Agency. 1980b. Test Methods for the Evaluation of Solid Waste, Physical/Chemical Methods. SW-646. Office of Water and Waste Management, Washington, D. C. 584 pp.

Wilson, F. R. 1975. Impact of Land Disposal of Sludges on Groundwater. Proceedings of the 1975 National Conference on Municipal Sludge Management and Disposal. Information Transfer, Inc. Rockville, Md. 193-199 pp.

APPENDIX A

DATA SET FOR METALS, ANIONS, AND TOTAL ORGANIC CARBON

Table A-1 presents the actual concentrations of metals, anions, and total organic carbon for leachate samples collected from the blank leach vessels. All three replicates are included.

Tables A-2 through A-8 give the actual concentrations of metals, anions, and total organic carbon. The data have been blank corrected and are presented in order of sludge type and treatment process. Table A-9 lists the reservoir blank values for which all previous tables have been corrected. All three replicates are included in all tables.

The derived data sets used in data analyses include the following:

(1) Accumulated Mass Leached

(2) Total Mass Leached

(3) Accumulated Fraction Leached

(4) Total Fraction Leached

The accumulated mass leached was generated by taking the value leached on the test day for each sample and multiplying it by a factor to estimate the amount leached during the interval between testing days. The factor was a number that represented the number of days in the test interval, the test day being the midpoint. The estimated values were then sequentially summed to generate the accumulated mass leached. The total mass leached was the accumulated mass leached on the last day of testing.

The accumulated fraction leached was determined by dividing each value of the accumulated mass leached file by the total amount available for leaching in each test sample. The total fraction leached was the accumulated fraction leached on the last day of testing.

TABLE A-1. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM BLANK LEACH VESSELS

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	B*	B	0.0011	B	0.008	B	B	B	B	B	B	B	B
1	2	B	B	0.0002	B	0.010	B	B	B	B	B	B	B	B
1	3	B	B	0.0010	0.002	0.002	B	B	B	B	B	B	B	B
7	1	B	B	0.0006	0.006	0.004	B	B	B	B	B	10	B	B
7	2	B	B	0.0010	0.005	0.007	B	B	B	B	B	10	B	B
7	3	B	B	0.0001	0.005	0.003	B	B	B	B	B	10	B	B
14	1	B	B	0.0003	0.003	0.002	B	B	B	B	B	N†	N	B
14	2	B	B	0.0007	0.007	B	B	B	B	B	B	N	N	B
14	3	B	B	0.0011	0.006	B	B	B	B	B	B	N	N	B
21	1	B	B	0.0003	B	B	B	B	B	B	B	B	B	B
21	2	B	B	0.0011	0.001	B	B	B	B	B	B	B	B	B
21	3	B	B	0.0002	0.002	B	B	B	B	B	B	11	B	B
28	1	B	B	0.0004	B	B	B	B	0.001	B	B	B	B	B
28	2	B	B	0.0006	0.001	B	B	0.002	B	B	B	B	B	B
28	3	B	B	0.0004	B	B	B	B	0.002	B	B	B	B	B
42	1	B	B	B	0.003	B	B	B	B	B	B	B	B	B
42	2	B	B	B	0.001	B	B	B	0.002	B	B	B	B	B
42	3	B	B	B	0.001	B	B	B	0.001	B	B	B	B	B
56	1	B	B	0.0002	B	0.002	B	B	0.001	B	B	B	B	B
56	2	B	B	0.0006	B	0.002	B	B	0.001	B	B	B	B	B
56	3	B	B	0.0004	0.002	0.002	B	B	0.001	B	B	B	B	B
86	1	B	B	0.0002	0.001	B	B	0.001	0.002	B	B	B	B	B
86	2	B	B	B	0.001	0.014	B	0.001	B	B	B	B	B	B
86	3	B	B	B	0.001	B	B	0.002	0.006	B	B	12	B	B

* B = below detection limits

† N = not determined

TABLE A-2. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM UNTREATED IMHOFF SLUDGE

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	B*	B	0.1110	0.004	0.138	B	0.002	0.638	B	3.480	305	28	28.0
1	2	B	B	0.1220	0.005	0.145	B	0.002	0.679	B	3.870	315	28	38.0
1	3	B	B	0.1070	0.006	0.142	B	0.002	0.610	B	3.350	295	22	16.0
7	1	B	B	0.0290	0.005	0.052	B	0.002	0.183	B	1.760	90	B	3.0
7	2	B	B	0.0420	0.005	0.058	0.057	0.004	0.249	B	2.040	122	B	3.2
7	3	B	B	0.0520	0.004	0.056	0.052	B	0.257	B	2.210	132	B	3.8
14	1	B	B	0.0260	0.002	0.034	B	B	0.089	B	1.030	31	B	2.4
14	2	B	B	0.0190	0.002	0.030	B	0.002	0.086	B	0.930	31	B	2.0
14	3	B	B	0.0240	0.003	0.050	B	0.002	0.094	B	1.010	35	B	2.3
21	1	B	B	0.0250	0.003	0.028	0.069	0.002	0.100	B	1.090	26	B	B
21	2	B	B	0.0180	0.001	0.026	0.050	B	0.063	B	0.740	10	B	B
21	3	B	B	0.0170	0.002	0.030	0.050	0.001	0.080	B	0.834	16	B	B
28	1	B	B	0.0312	0.003	0.040	0.160	B	0.095	B	1.200	B	B	B
28	2	B	B	0.0252	0.002	0.030	0.137	B	0.064	B	0.793	B	B	B
28	3	B	B	0.0188	0.002	0.030	0.098	B	0.074	B	0.920	B	B	B
42	1	B	B	0.0360	0.004	0.040	0.349	B	0.129	B	1.790	B	B	N†
42	2	B	B	0.0152	0.003	0.032	0.593	B	0.097	B	1.230	B	B	N
42	3	B	B	0.0244	0.003	0.026	0.149	B	0.074	B	0.920	B	B	N
56	1	0.018	B	0.0310	0.003	0.046	0.310	B	0.101	B	1.460	B	B	1.5
56	2	0.032	B	0.0250	0.003	0.037	1.050	0.001	0.083	B	1.060	B	B	B
56	3	0.033	B	0.0210	0.002	0.038	0.514	B	0.078	B	0.938	B	B	1.9
86	1	0.007	B	0.0680	0.042	0.051	0.615	0.020	0.072	B	1.290	B	B	N
86	2	B	B	0.0450	0.004	0.027	2.280	0.004	0.081	B	1.190	B	B	N
86	3	0.015	B	0.0340	0.003	0.027	1.010	0.002	0.078	B	1.030	B	B	N

* B = below detection limits

† N = not determined

TABLE A-3. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM IMHOFF SLUDGE TREATED BY PROCESS XA

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	0.008	B	0.0051	0.203	0.476	0.078	B	0.002	B	B	64	6	30.0
1	2	0.008	B	0.0011	0.195	0.543	0.079	B	0.002	B	B	80	B	29.0
1	3	0.008	B	0.0010	0.191	0.514	0.076	B	B	B	B	70	11	28.0
7	1	B*	B	0.0004	0.002	0.014	B	B	0.007	B	B	B	B	1.4
7	2	B	B	0.0002	0.003	0.016	B	B	0.010	B	B	B	B	1.6
7	3	B	B	0.0011	0.002	0.016	B	0.001	0.005	B	B	B	B	2.1
14	1	B	B	0.0007	0.007	0.001	B	B	0.013	B	B	N†	N	1.0
14	2	B	B	0.0004	0.007	0.006	B	B	0.008	B	B	N	N	1.2
14	3	0.004	B	0.0024	0.008	0.002	B	B	0.007	B	B	N	N	1.3
21	1	B	B	0.0005	0.002	0.005	B	B	0.016	B	B	B	B	1.0
21	2	B	B	0.0013	0.001	0.005	B	B	0.012	B	B	B	B	1.2
21	3	B	B	0.0029	0.003	0.045	B	B	0.022	B	0.103	B	B	1.4
28	1	B	B	0.0016	0.001	0.010	B	B	0.019	B	B	B	B	B
28	2	B	B	0.0014	0.001	0.008	B	0.001	0.012	B	B	B	B	B
28	3	B	B	0.0012	0.001	0.006	B	B	0.015	B	B	B	B	1.0
42	1	B	B	0.0008	0.002	0.004	B	B	0.016	B	B	B	B	B
42	2	B	B	0.0010	0.004	0.006	B	B	0.014	B	0.052	B	B	1.2
42	3	B	B	0.0014	0.002	0.006	B	B	0.015	0.010	0.015	B	B	1.8
56	1	B	B	0.0014	B	0.006	B	B	0.011	0.025	B	B	B	B
56	2	B	B	0.0012	B	0.006	B	0.001	0.013	0.010	B	B	B	B
56	3	B	B	0.0012	B	0.010	B	B	0.012	B	B	B	B	B
86	1	B	B	0.0018	0.003	B	B	0.001	0.027	B	0.105	12	B	B
86	2	B	B	0.0016	0.001	0.004	0.161	B	0.041	0.011	0.112	12	B	B
86	3	B	B	0.0020	0.002	0.010	B	B	0.023	B	0.097	12	B	B

* B = below detection limits

† N = not determined

TABLE A-4. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM IMHOFF SLUDGE TREATED BY PROCESS XB

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	0.003	B	0.0030	0.628	2.270	0.118	0.001	0.005	B	B	155	17	125.0
1	2	0.002	B	0.0048	0.650	1.610	0.107	B	0.005	0.001	B	130	11	87.0
1	3	0.002	B	0.0030	0.583	2.070	0.138	B	0.004	0.001	B	135	11	89.0
7	1	0.004	B	0.0035	0.005	0.064	B	B	0.037	B	0.089	9	B	3.9
7	2	B*	B	0.0047	0.004	0.065	B	B	0.018	B	0.102	9	B	4.7
7	3	B	B	0.0032	0.006	0.077	B	B	0.016	B	0.080	9	B	4.9
14	1	B	B	0.0022	0.003	0.061	B	B	0.025	B	0.110	N†	N	3.6
14	2	B	B	0.0033	0.003	0.034	B	B	0.021	B	0.080	N	N	4.1
14	3	B	B	0.0025	0.003	0.054	B	B	0.021	B	0.087	11	B	3.9
21	1	B	B	0.0005	0.002	0.005	B	B	0.015	B	B	B	B	1.8
21	2	B	B	0.0030	0.003	0.053	B	B	0.024	B	0.095	B	B	3.0
21	3	B	B	0.0062	0.005	0.059	B	B	0.026	B	0.098	B	B	3.2
28	1	B	B	0.0034	0.002	0.048	B	B	0.014	B	0.114	11	B	1.5
28	2	B	B	0.0028	0.001	0.048	B	B	0.027	B	0.108	10	B	1.8
28	3	B	B	0.0028	0.003	0.056	B	B	0.019	B	0.107	11	B	2.0
42	1	B	B	0.0026	0.003	0.028	B	B	0.018	B	0.161	B	B	1.5
42	2	B	B	0.0038	0.005	0.024	0.135	B	0.027	B	0.142	8	B	1.7
42	3	B	B	0.0034	0.002	0.030	0.194	0.002	0.031	B	0.140	15	B	1.6
56	1	B	B	0.0020	B	0.012	B	B	0.021	B	0.097	10	B	B
56	2	B	B	0.0024	B	0.012	0.077	B	0.020	B	0.098	10	B	B
56	3	B	B	0.0036	B	B	0.191	B	0.018	B	0.119	10	B	1.0
86	1	B	B	0.0054	0.001	0.026	B	B	0.054	B	0.243	12	B	1.1
86	2	B	B	0.0074	0.003	0.016	0.410	0.001	0.050	B	0.261	12	B	1.3
86	3	B	B	0.0052	0.003	0.006	0.659	0.003	0.043	B	0.240	12	B	2.1

* B = below detection limits

† N = not determined

TABLE A-5. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM UNTREATED INCINERATOR ASH

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	B*	B	0.0004	0.044	0.053	B	0.002	0.082	B	B	92	17	20.0
1	2	B	B	0.0006	0.073	0.053	B	0.002	0.080	B	0.221	185	22	6.1
1	3	0.010	B	0.0008	0.052	0.057	B	0.004	0.104	B	B	338	22	8.4
7	1	B	B	0.0002	0.001	0.010	B	0.002	0.088	B	B	10	B	1.5
7	2	B	B	0.0004	0.002	0.008	B	0.002	0.103	B	B	B	B	B
7	3	B	B	0.0006	0.002	0.010	B	0.002	0.125	B	B	B	B	B
14	1	B	B	0.0004	B	0.012	B	0.004	0.056	B	B	B	B	B
14	2	B	B	0.0004	B	0.008	B	0.060	B	B	B	B	B	B
14	3	B	B	0.0004	0.001	0.010	B	0.006	0.082	B	B	B	B	B
21	1	B	B	0.0002	B	0.012	B	B	0.062	B	B	B	B	1.1
21	2	B	B	0.0004	B	0.016	B	B	0.101	B	0.053	B	B	1.4
21	3	B	B	0.0002	B	0.014	B	0.002	0.078	B	B	B	B	1.6
28	1	B	B	0.0004	0.001	0.008	B	B	0.066	B	B	B	B	B
28	2	B	B	0.0002	B	0.016	B	B	0.069	B	0.053	B	B	B
28	3	B	B	0.0004	0.001	0.012	B	B	0.063	B	0.050	B	B	B
42	1	B	B	0.0004	0.001	0.024	B	B	0.084	B	0.069	B	B	N**
42	2	B	B	0.0004	0.001	0.026	B	B	0.075	B	0.082	B	B	N
42	3	B	B	0.0004	0.001	0.022	B	B	0.066	B	0.082	B	B	N
56	1	0.028	B	0.0005	B	0.038	B	0.003	0.047	B	0.055	B	B	B
56	2	B	B	0.0009	B	0.043	B	0.004	0.077	B	0.070	B	B	B
56	3	0.013	B	0.0007	0.001	0.042	B	0.003	0.054	B	0.073	B	B	B
86	1	B	B	0.0004	B	0.044	B	0.004	0.029	B	0.052	B	B	N
86	2	0.012	B	0.0004	0.002	0.044	B	0.004	0.029	B	0.063	B	B	N
86	3	0.011	B	0.0010	B	0.046	B	0.018	0.030	B	0.059	B	B	N

* B = below detection limits

** N = not determined

TABLE A-6. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM INCINERATOR ASH TREATED BY PROCESS X

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	B*	B	0.0005	0.085	0.006	B	B	0.008	B	B	112	11	2.5
1	2	B	B	0.0002	0.083	0.024	B	B	0.010	B	B	80	11	2.3
1	3	B	B	0.0009	0.098	0.013	B	B	0.009	B	B	98	11	2.0
7	1	B	B	0.0019	B	0.003	B	B	0.028	B	B	B	B	B
7	2	B	B	0.0003	0.004	0.011	B	B	0.037	B	B	B	B	B
7	3	B	B	0.0004	0.005	0.001	B	B	0.021	B	B	B	B	B
14	1	B	B	0.0005	0.004	B	B	B	0.031	B	B	B	B	1.1
14	2	B	B	0.0003	0.003	0.001	B	B	0.044	B	B	B	B	1.0
14	3	B	B	0.0004	0.003	0.001	B	B	0.037	B	B	B	B	1.0
21	1	B	B	0.0004	0.003	0.003	B	B	0.038	B	B	B	B	1.1
21	2	B	B	0.0004	0.004	0.004	B	B	0.038	B	B	B	B	1.0
21	3	B	B	0.0010	0.004	0.007	B	B	0.032	B	B	B	B	B
28	1	B	B	B	B	B	B	B	0.036	B	B	B	B	B
28	2	B	B	0.0002	0.002	B	B	B	0.043	B	B	B	B	B
28	3	B	B	0.0002	0.002	0.004	B	B	0.034	B	B	B	B	B
42	1	B	B	0.0002	0.002	B	B	B	0.036	B	B	B	B	B
42	2	B	B	0.0002	0.002	0.004	B	B	0.039	B	B	B	B	B
42	3	B	B	0.0002	0.002	0.004	B	B	0.034	B	B	B	B	B
56	1	B	B	0.0002	B	0.020	B	0.002	0.035	B	B	B	B	B
56	2	B	B	0.0002	B	0.002	B	0.002	0.030	B	B	B	B	B
56	3	B	B	0.0004	0.006	B	B	0.001	0.044	B	B	10	B	B
86	1	B	B	0.0006	0.001	0.002	B	B	0.052	B	B	14	B	B
86	2	B	B	0.0012	0.002	0.002	B	B	0.063	B	B	B	B	B
86	3	B	B	0.0008	0.003	0.002	B	0.001	0.057	B	B	B	B	B

* B = below detection limits

TABLE A-7. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM INCINERATOR ASH TREATED BY PROCESS Y

Days elapsed	Replicate	As (mg/1)	Be (mg/1)	Cd (mg/1)	Cr (mg/1)	Cu (mg/1)	Fe (mg/1)	Pb (mg/1)	Mn (mg/1)	Se (mg/1)	Zn (mg/1)	SO_4 (mg/1)	Cl (mg/1)	TOC (mg/1)
1	1	B*	B	0.0006	0.003	0.042	B	0.002	B	B	B	11	B	5.7
1	2	B	B	0.0016	0.004	0.013	B	B	0.001	B	B	B	B	3.1
1	3	B	B	0.0008	0.004	0.008	B	0.001	0.003	B	B	B	B	3.6
7	1	0.020	B	0.0006	0.003	0.006	B	0.002	0.009	B	B	B	B	B
7	2	0.037	B	0.0004	0.003	0.003	B	0.010	B	B	B	B	B	1.1
7	3	0.047	B	B	0.002	0.004	B	B	0.010	B	B	B	B	B
14	1	B	B	0.0003	0.002	0.002	B	B	0.001	B	B	B	B	B
14	2	0.012	B	0.0001	0.001	0.001	B	B	0.044	B	B	8	B	B
14	3	B	B	0.0002	0.001	B	B	B	0.002	B	B	B	B	B
21	1	B	B	0.0001	0.003	0.002	B	B	B	B	B	B	B	B
21	2	B	B	B	B	B	B	0.016	B	B	B	B	B	B
21	3	B	B	B	B	0.002	B	B	B	B	B	B	B	B
28	1	0.021	B	0.0004	B	B	B	B	0.005	B	B	B	B	B
28	2	0.029	B	0.0001	B	B	B	B	0.001	B	B	16	B	B
28	3	0.015	B	0.0003	B	B	B	0.002	0.002	B	B	B	B	B
42	1	0.019	B	0.0002	B	B	B	B	B	B	B	B	B	B
42	2	B	B	0.0002	0.001	B	B	B	B	B	B	B	B	B
42	3	B	B	0.0002	0.001	0.001	B	0.003	B	B	B	B	B	B
56	1	B	B	0.0002	B	0.000	B	B	B	B	B	B	B	B
56	2	B	B	0.0002	B	B	B	B	B	B	B	B	B	B
56	3	B	B	0.0003	B	B	B	B	B	B	B	B	B	1.0
86	1	B	B	B	B	B	B	B	B	B	B	B	B	B
86	2	B	B	B	B	B	B	B	B	B	B	B	B	B
86	3	B	B	B	B	B	B	0.000	B	B	B	B	B	B

* B = below detection limits

TABLE A-8. LEACHING LOSS OF METALS, ANIONS AND TOTAL ORGANIC CARBON FROM INCINERATOR ASH TREATED BY PROCESS Z

Days elapsed	Replicate	As (mg/1)	Be (mg/1)	Cd (mg/1)	Cr (mg/1)	Cu (mg/1)	Fe (mg/1)	Pb (mg/1)	Mn (mg/1)	Se (mg/1)	Zn (mg/1)	SO_4 (mg/1)	Cl (mg/1)	TOC (mg/1)
1	1	0.015	B*	0.0008	0.002	0.012	B	0.006	0.400	B	B	360	B	N
1	2	0.007	B	0.0008	0.002	0.014	B	0.004	0.377	B	B	360	B	N
1	3	0.014	B	0.0008	0.002	0.005	B	0.006	0.223	B	B	200	B	N
7	1	0.020	B	0.0007	0.001	0.016	B	B	0.274	B	B	190	B	B
7	2	0.026	B	0.0007	0.001	0.024	B	B	0.256	B	B	175	B	B
7	3	0.037	B	0.0006	B	0.014	B	0.005	0.263	B	B	185	B	B
14	1	N**	N	N	N	N	N	N	N	N	B	135	B	2.8
14	2	N	N	N	N	N	N	N	N	N	B	125	B	1.5
14	3	N	N	N	N	N	N	N	N	N	B	130	B	B
21	1	B	B	0.0041	B	0.024	B	B	0.116	B	B	110	B	N
21	2	0.023	B	0.0028	B	0.016	B	B	0.112	B	B	108	B	N
21	3	0.028	B	0.0013	B	0.022	0.146	B	0.103	B	B	92	B	N
28	1	B	B	0.0012	B	0.019	0.052	0.007	0.165	B	B	96	B	B
28	2	0.021	B	0.0009	0.001	0.015	B	0.003	0.166	B	B	84	B	B
28	3	0.038	B	0.0005	0.001	0.010	0.096	0.002	0.168	B	B	90	B	B
42	1	0.024	B	0.0006	0.002	0.027	0.086	0.015	0.112	B	B	62	B	B
42	2	0.032	B	0.0007	0.001	0.015	B	0.010	0.128	B	B	78	B	B
42	3	0.030	B	0.0005	0.001	0.011	0.218	0.009	0.136	B	B	64	B	B
56	1	0.068	B	0.0008	B	0.024	0.132	0.018	0.114	B	B	62	B	1.8
56	2	0.064	B	0.0007	B	0.020	B	0.012	0.114	B	0.068	72	B	1.5
56	3	0.051	B	0.0007	B	0.020	0.329	0.024	0.126	B	0.063	76	B	1.3
86	1	B	B	0.0012	B	0.005	B	0.001	0.095	B	B	65	B	B
86	2	B	B	0.0012	B	0.004	B	0.002	0.086	B	B	75	B	B
86	3	B	B	0.0010	B	0.002	B	B	0.098	B	B	60	B	B

* B = below detection limits

** N = not determined

TABLE A-9. RESERVOIR BLANK VALUES OF METALS, ANIONS AND TOTAL ORGANIC CARBON FOR WHICH ALL PRECEDING HAVE BEEN CORRECTED

Days elapsed	Replicate	As (mg/l)	Be (mg/l)	Cd (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Mn (mg/l)	Se (mg/l)	Zn (mg/l)	SO_4 (mg/l)	Cl (mg/l)	TOC (mg/l)
1	1	B*	B	B	0.001	B	B	B	B	B	B	B	B	B
7	1	B	B	B	B	B	B	B	B	B	B	B	B	B
14	1	B	B	B	B	B	B	B	B	B	B	B	B	B
21	1	B	B	B	0.002	B	B	B	B	B	B	B	B	B
28	1	B	B	B	0.001	B	B	B	B	B	B	B	B	B
42	1	B	B	0.0002	B	B	B	0.006	B	B	B	B	B	B
56	1	B	B	B	B	B	B	0.002	B	B	B	B	B	B
86	1	B	B	0.0006	B	B	B	B	B	B	B	N	N	B

* B = below detection limits

APPENDIX B

DATA SET FOR pH AND CONDUCTIVITY

Tables B-1 through B-4 give the actual pH and conductivity values for each one-liter sample collected. The conductivity data have been blank corrected and are presented for all waste types and treatment processes.

Derived data sets used in data analyses included the following:

(1) Average pH and conductivity values for each day.

(2) Average weekly pH and conductivity values.

The average pH was determined by taking the antilogarithm of the pH values, averaging the resultant numbers, and then taking the log of the mean which is the final average pH value. Simple arithmetic means were made of the daily conductivity values.

The average weekly conductivity was determined by specifying weekly midpoints to generate a data set composed of weekly conductivity means. In this way, each weekly mean value represents a five weekday leachate renewal and collection period.

TABLE B-1. DAILY pH VALUES OF LEACHATE SAMPLES FROM VESSELS CONTAINING IMHOFF SLUDGES (TREATED AND UNTREATED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
1	5.2	5.3	5.3	6.4	6.5	6.5	6.0	6.0	5.9
2	5.6	5.6	5.6	6.1	6.2	6.1	5.8	5.8	5.8
3	5.6	5.6	5.6	5.8	5.9	5.9	5.7	5.6	5.6
4	5.4	5.3	5.3	5.8	5.9	5.9	5.7	5.6	5.6
6	N*	N	N	N	N	N	N	N	N
7	5.5	5.5	5.5	5.7	5.8	5.9	5.8	5.7	5.8
8	5.5	5.5	5.4	5.8	5.8	6.0	6.0	6.0	5.9
9	5.2	5.2	5.2	N	N	N	N	N	N
10	5.2	.53	5.3	5.6	5.8	5.8	5.8	5.7	5.8
11	5.1	5.2	5.2	N	N	N	N	N	N
13	N	N	N	5.7	5.6	5.8	5.8	5.8	5.9
14	5.4	5.4	5.5	5.4	5.6	5.6	5.5	5.5	5.6
15	5.2	5.2	5.3	5.6	5.7	5.7	5.8	5.8	5.8
16	5.2	5.2	5.2	5.7	5.7	5.7	5.7	5.6	5.6
17	5.1	5.1	5.2	5.4	5.5	5.5	5.4	5.4	5.4
18	5.2	5.2	5.2	N	N	N	N	N	N
20	N	N	N	5.8	6.0	6.0	6.1	6.1	6.1
21	5.4	5.4	5.5	5.5	5.6	5.6	5.6	5.5	5.6
22	5.2	5.1	5.2	5.8	5.8	5.8	5.8	5.7	5.7
23	5.3	5.2	5.2	5.5	5.6	5.6	5.5	5.5	5.5
24	5.2	5.2	5.2	5.5	5.5	5.5	5.5	5.5	5.5
25	5.2	5.1	5.2	N	N	N	N	N	N
27	N	N	N	6.0	6.0	6.0	6.0	6.0	6.0
28	5.4	5.4	5.4	5.5	5.6	5.6	5.5	5.5	5.5
29	5.2	5.1	5.2	5.6	5.6	5.6	5.5	5.5	5.6
30	5.1	5.1	5.1	5.5	5.5	5.5	5.4	5.5	5.5
31	5.1	5.1	5.1	5.5	5.5	5.5	5.5	5.5	5.5
32	5.2	5.1	5.1	N	N	N	N	N	N
34	N	N	N	N	N	N	N	N	N
35	5.3	5.2	5.3	5.0	5.1	5.1	5.0	5.0	5.1
36	5.3	5.2	5.1	5.3	5.3	5.4	5.4	5.3	5.4
37	4.9	4.8	4.9	5.4	5.4	5.4	5.4	5.4	5.4
38	5.0	4.9	4.9	5.4	5.4	5.4	5.4	5.4	5.4
39	4.9	4.8	4.8	N	N	N	N	N	N
41	N	N	N	5.8	5.8	5.8	5.9	5.8	5.8
42	5.2	5.2	5.2	5.1	5.2	5.2	5.2	5.2	5.2
43	5.1	5.1	4.9	5.3	5.3	5.3	5.4	5.4	5.4
44	5.0	4.9	4.9	5.5	5.5	5.5	5.5	5.5	5.5

(Continued)

* N = not determined.

TABLE B-1. (CONCLUDED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
45	5.5	5.5	5.4	5.4	5.4	5.5	5.5	5.5	5.5
46	4.9	4.9	4.8	N	N	N	N	N	N
48	N	N	N	5.7	5.7	5.8	5.8	5.8	5.8
49	5.3	5.2	5.2	5.3	5.4	5.3	5.3	5.2	5.2
50	4.9	5.0	4.9	5.3	5.3	5.3	5.4	5.4	5.4
51	5.0	4.9	4.9	5.3	5.3	5.3	5.4	5.4	5.4
52	5.0	4.9	4.9	5.2	5.3	5.4	5.4	5.4	5.4
53	5.1	5.1	5.0	N	N	N	N	N	N
55	N	N	N	5.7	5.8	5.9	5.8	5.8	5.9
56	5.1	5.1	5.2	5.4	5.4	5.5	5.4	5.4	5.4
57	5.1	5.0	4.9	5.4	5.4	5.5	5.5	5.4	5.5
58	4.8	4.8	4.8	5.2	5.2	5.3	5.4	5.4	5.4
59	4.5	4.4	4.3	5.3	5.3	5.4	5.3	5.4	5.4
60	4.9	4.9	4.8	N	N	N	N	N	N
62	N	N	N	5.9	5.9	5.9	5.9	5.8	5.9
63	4.9	5.0	4.9	5.2	5.3	5.3	5.3	5.2	5.3
64	4.7	4.8	4.7	5.5	5.6	5.6	5.6	5.6	5.6
65	4.4	4.6	4.5	5.4	5.4	5.5	5.4	5.4	5.4
66	4.5	4.4	4.3	5.5	5.4	5.4	5.4	5.4	5.4
67	4.0	4.0	4.0	N	N	N	N	N	N
68	N	N	N	5.8	5.8	5.9	5.8	5.8	5.9
70	4.7	4.5	4.5	5.4	5.5	5.5	5.5	5.4	5.4
71	4.4	4.4	4.4	5.3	5.4	5.4	5.3	5.3	5.3
72	4.7	4.6	4.5	5.2	5.4	5.4	5.3	5.3	5.3
73	4.2	4.3	4.3	5.4	5.4	5.4	5.4	5.3	5.4
74	4.2	4.3	4.2	N	N	N	N	N	N
76	N	N	N	5.7	5.8	5.8	5.8	5.7	5.8
77	4.3	4.4	4.4	5.2	5.2	5.4	5.3	5.3	5.3
78	N	N	N	5.2	5.3	5.2	5.2	5.2	5.2
79	4.4	4.4	4.3	5.2	5.3	5.2	5.2	5.2	5.2
80	4.3	4.5	4.4	4.9	5.1	5.1	5.2	5.2	5.1
81	4.0	4.1	4.1	N	N	N	N	N	N
83	N	N	N	5.6	5.7	5.7	5.7	5.7	5.7
84	4.7	4.5	4.5	5.0	5.2	5.2	5.2	5.2	5.2
85	4.1	4.2	4.1	5.2	5.2	5.2	5.2	5.1	5.2
86	4.2	4.1	4.0	5.2	5.3	5.2	5.1	5.2	5.1
87	4.6	4.1	4.1	5.3	5.4	5.3	5.2	5.2	5.2
88	4.4	4.6	4.2	N	N	N	N	N	N
90	N	N	N	5.6	5.7	5.8	5.7	5.7	5.6
91	N	N	N	N	N	N	N	N	N

TABLE B-2. DAILY CONDUCTIVITY VALUES OF LEACHATE SAMPLES FROM VESSELS CONTAINING IMHOFF SLUDGES (TREATED AND UNTREATED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
1	1057	957	1057	1057	957	1057	796	686	696
2	1155	1255	1255	1155	1255	1255	538	458	508
3	959	959	959	959	959	959	409	289	309
4	456	456	456	456	456	456	N	N	N
6	N*	N	N	N	N	N	476	436	446
7	635	635	795	635	635	795	254	254	254
8	189	264	269	189	264	269	172	142	152
9	171	251	371	171	251	371	N	N	N
10	172	262	362	172	262	362	280	200	240
11	174	194	314	174	194	314	N	N	N
13	N	N	N	N	N	N	451	401	391
14	440	390	440	440	390	440	229	209	239
15	148	158	228	148	158	228	130	110	120
16	143	113	163	143	113	163	286	236	256
17	133	103	153	133	103	153	165	125	155
18	152	102	142	152	102	142	N	N	N
20	N	N	N	N	N	N	410	340	420
21	201	121	171	201	121	171	174	184	204
22	122	62	82	122	62	82	101	101	111
23	159	69	99	159	69	99	189	189	209
24	138	78	78	138	78	78	172	172	162
25	91	51	71	91	51	71	N	N	N
27	N	N	N	N	N	N	377	397	437
28	149	79	9	149	79	99	189	179	189
29	88	68	88	88	68	88	90	90	90
30	77	47	47	77	47	47	169	169	170
31	81	51	71	81	51	71	159	169	159
32	81	51	61	81	51	61	N	N	N
34	N	N	N	N	N	N	378	348	368
35	90	70	80	90	70	80	98	88	118
36	80	70	70	80	70	70	150	120	160
37	50	30	150	50	30	150	150	150	180
38	40	40	40	40	40	40	131	151	151
39	30	10	10	30	10	10	N	N	N
41	N	N	N	N	N	N	347	297	297
42	60	60	70	60	60	70	137	137	127
43	50	50	20	50	50	20	245	145	175
44	50	40	30	50	40	30	139	149	179

(Continued)

* All values are in μmhos/cm. N = not determined.

TABLE B-2. (CONCLUDED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
45	N	N	N	N	N	N	86	96	96
46	60	30	30	60	30	30	N	N	N
48	N	N	N	N	N	N	335	335	355
49	70	90	90	70	90	90	124	97	97
50	30	20	20	30	20	20	121	111	141
51	110	160	160	110	160	160	112	142	152
52	50	30	20	50	30	20	114	124	134
53	470	200	90	470	200	90	N	N	N
55	N	N	N	N	N	N	310	320	350
56	530	220	130	530	220	130	108	118	138
57	730	290	110	730	290	110	103	113	113
58	60	70	90	60	70	90	113	123	113
59	-60	-90	-110	-60	-90	-110	82	102	102
60	45	150	140	45	150	140	N	N	N
62	N	N	N	N	N	N	281	281	301
63	180	130	280	180	130	280	52	62	82
64	-30	10	-50	-30	10	-50	139	149	179
65	130	40	50	130	40	50	108	118	138
66	50	40	50	130	40	50	108	118	138
67	40	10	20	40	10	20	N	N	N
69	N	N	N	N	N	N	129	279	279
70	80	50	60	80	50	60	118	118	128
71	0	30	0	0	30	0	117	107	137
72	60	30	30	60	30	30	101	111	111
73	60	70	40	60	70	40	91	81	141
74	60	50	30	60	50	30	N	N	N
76	N	N	N	N	N	N	300	260	290
77	80	70	50	80	70	50	110	110	130
78	N	N	N	N	N	N	110	100	130
80	70	50	40	70	50	40	60	50	50
81	40	20	30	40	20	30	N	N	N
83	N	N	N	N	N	N	280	280	320
84	289	99	89	289	99	89	90	90	120
85	92	52	2	92	52	2	110	100	110
86	25	-5	-10	25	-5	-10	98	98	108
87	25	5	-10	25	5	-10	N	N	N
88	72	48	-6	72	48	-6	N	N	N
90	N	N	N	N	N	N	160	160	160
91	N	N	N	N	N	N	N	N	N

Negative conductivity values result from correction for conductivity of blank; they can be ignored.

TABLE B-3. DAILY pH VALUES OF LEACHATE SAMPLES FROM VESSELS CONTAINING INCINERATOR ASH SLUDGES (TREATED AND UNTREATED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
1	5.6	5.8	5.9	5.7	5.7	5.6	5.1	5.0	5.1
2	6.0	6.1	6.1	5.6	5.5	5.5	5.2	5.1	5.0
3	5.9	5.9	5.9	5.5	5.5	5.5	5.0	5.1	5.2
4	5.4	5.5	5.5	N	N	N	N	N	N
6	N*	N	N	N	N	N	N	N	N
7	5.8	5.9	5.8	5.8	5.7	5.8	5.0	5.1	5.1
8	5.6	5.8	5.7	5.9	5.9	6.0	4.7	4.8	4.8
9	5.4	5.4	5.5	N	N	N	4.6	4.7	4.8
10	5.3	5.4	5.4	5.7	5.7	5.7	4.8	4.7	4.5
11	5.3	5.4	5.4	N	N	N	N	N	N
13	N	N	N	5.7	5.7	5.8	5.3	5.4	5.5
14	5.6	5.6	5.6	5.4	5.5	5.4	4.7	4.8	4.9
15	5.4	5.4	5.4	5.8	5.8	5.8	4.5	4.6	4.6
16	5.3	5.3	5.4	5.6	5.6	5.5	4.6	4.7	4.7
17	5.2	5.2	5.5	5.4	5.4	5.3	4.5	4.6	4.7
18	5.3	5.2	5.2	N	N	N	N	N	N
20	N	N	N	6.0	6.0	6.0	5.3	5.2	5.2
21	5.4	5.3	5.3	5.5	5.5	5.5	5.0	4.8	4.8
22	5.1	5.1	5.0	5.8	5.7	5.7	5.0	5.0	5.0
23	5.2	5.0	5.0	5.5	5.4	5.4	5.1	4.9	4.9
24	5.1	5.0	5.0	5.4	5.4	5.4	4.6	4.7	4.7
25	5.0	4.9	4.9	N	N	N	N	N	N
27	N	N	N	6.0	6.0	6.0	4.9	5.0	5.1
28	5.3	5.1	5.1	5.5	5.5	5.4	4.6	4.6	4.5
29	5.0	5.0	4.9	5.6	5.6	5.6	4.6	4.3	4.2
30	4.9	4.9	4.9	5.4	5.4	5.4	4.3	4.3	4.3
31	4.9	4.8	4.7	5.4	5.4	5.4	4.5	4.4	4.5
32	4.9	4.7	4.7	N	N	N	N	N	N
34	N	N	N	6.1	6.2	6.1	N	N	N
35	5.0	4.9	4.9	5.0	5.0	5.0	5.0	4.9	5.0
36	4.8	4.7	4.7	5.3	5.3	5.2	4.1	4.3	4.1
37	4.7	4.5	4.5	5.4	5.4	5.4	4.4	4.2	4.1
38	4.6	4.5	4.5	5.3	5.3	5.3	4.2	4.1	4.0
39	4.6	4.5	4.5	N	N	N	N	N	N
41	N	N	N	5.8	5.8	5.8	5.0	5.0	5.0
42	4.9	4.8	4.8	5.3	5.2	5.2	4.3	4.2	4.3
43	4.6	4.6	4.6	5.4	5.3	5.2	3.9	3.9	4.1
44	4.6	4.5	4.4	5.4	5.4	5.4	4.2	4.2	4.2

(Continued)

* N = not determined.

TABLE B-3. (CONCLUDED)

Days of Leaching	Untreated Replicates			Process XA Replicates			Process XB Replicates		
	1	2	3	1	2	3	1	2	3
45	5.1	5.0	4.9	5.4	5.4	5.4	4.0	3.8	3.7
46	4.5	4.4	4.4	N	N	N	N	N	N
48	N	N	N	5.7	5.8	5.7	4.7	4.6	4.5
49	4.8	4.8	4.6	5.3	5.1	5.2	4.4	4.3	4.1
50	4.5	4.5	4.5	5.3	5.3	5.2	4.1	4.0	3.9
51	4.4	4.3	4.3	5.4	5.4	5.4	4.0	3.8	3.7
52	4.5	4.4	4.4	5.4	5.4	5.3	4.5	4.4	4.3
53	4.6	4.5	4.5	N	N	N	N	N	N
55	N	N	N	5.8	5.8	5.8	4.7	4.5	4.6
56	4.7	4.6	4.5	5.4	5.3	5.3	4.5	4.5	4.6
57	4.4	4.1	4.2	5.4	5.4	5.3	4.5	4.4	4.3
58	4.3	4.4	4.3	5.3	5.3	5.3	4.1	3.9	4.0
59	3.8	3.7	3.7	5.2	5.2	5.2	4.6	4.3	4.3
60	4.2	4.3	4.3	N	N	N	N	N	N
62	N	N	N	5.8	5.8	5.8	4.6	4.5	4.5
63	4.7	4.6	4.5	5.1	5.1	5.1	4.0	3.9	3.9
64	4.2	4.2	4.1	5.4	5.4	5.4	3.9	4.0	3.9
65	4.0	3.9	3.9	5.4	5.3	5.3	4.1	3.8	3.8
66	3.9	3.8	3.7	5.3	5.3	5.3	4.1	4.0	3.7
67	3.6	3.6	3.6	N	N	N	N	N	N
69	N	N	N	5.8	5.8	5.8	4.6	4.4	4.5
70	4.0	3.9	3.7	5.2	5.3	5.3	4.2	4.0	3.9
71	4.1	3.8	3.8	5.3	5.3	5.2	4.5	4.4	4.5
72	4.1	4.0	4.0	5.3	5.3	5.2	4.3	4.1	4.1
73	3.7	3.6	3.6	5.3	5.3	5.2	4.2	3.9	3.9
74	3.7	3.5	3.6	N	N	N	N	N	N
76	N	N	N	5.6	5.7	5.6	4.6	4.1	4.2
77	3.9	3.7	3.7	5.2	5.2	5.0	4.1	3.7	3.7
78	N	N	N	5.2	5.2	5.1	4.2	3.9	4.0
79	3.9	3.7	3.6	5.0	5.1	5.0	4.1	3.9	4.0
80	4.0	3.8	3.8	4.9	4.9	4.9	4.2	3.9	4.0
81	3.6	3.5	3.5	N	N	N	N	N	N
83	N	N	N	5.6	5.7	5.7	4.6	4.5	4.5
84	4.1	3.9	3.9	5.1	5.1	5.2	4.2	4.0	3.8
85	3.6	3.5	3.5	5.1	5.0	5.0	4.3	4.0	4.1
86	3.5	3.4	3.4	4.9	4.9	4.9	4.1	3.8	3.8
87	3.6	3.5	3.4	5.0	5.0	5.0	4.1	3.8	4.1
88	4.3	4.1	3.8	N	N	N	N	N	N
90	N	N	N	5.8	5.7	5.7	4.2	4.3	4.4
91	N	N	N	N	N	N	4.3	4.0	4.0

TABLE B-4. DAILY CONDUCTIVITY VALUES OF LEACHATE SAMPLES FROM VESSELS CONTAINING IMHOFF SLUDGES (TREATED AND UNTREATED)

Days of Leaching	Untreated Replicates			Process X Replicates			Process Y Replicates			Process Z Replicates		
	1	2	3	1	2	3	1	2	3	1	2	3
1	557	697	817	466	466	436	155	125	115	1025	975	1045
2	855	955	955	378	338	338	101	71	71	1085	1005	1035
3	659	659	659	289	279	269	191	151	151	552	592	412
4	216	216	196	M	M	M	M	M	M	M	M	M
6	M	M	M	456	466	456	156	156	151	1070	1170	1250
7	415	435	375	244	254	244	84	84	79	660	630	660
8	122	137	142	142	152	152	88	98	98	520	560	540
9	131	191	191	M	M	M	102	107	92	350	390	390
10	102	152	162	250	240	220	89	99	89	447	557	507
11	154	154	124	M	M	M	M	M	M	M	M	M
13	M	M	M	411	341	341	206	181	161	770	930	1050
14	220	200	160	239	209	199	34	34	32	490	600	570
15	88	138	118	100	110	100	84	84	84	287	297	267
16	73	103	93	256	216	196	15	15	10	390	440	440
17	53	63	53	145	135	125	15	15	15	360	440	400
18	82	62	42	M	M	M	M	M	M	M	M	M
20	M	M	M	400	360	330	60	40	50	768	688	828
21	81	61	61	184	154	154	20	10	-5	421	441	441
22	42	32	22	91	101	101	20	15	20	245	235	195
23	59	19	29	189	189	159	10	10	15	285	295	295
24	58	18	28	172	152	142	10	10	15	329	349	329
25	21	21	21	M	M	M	M	M	M	M	M	M
27	M	M	M	407	387	357	30	20	35	722	672	722
28	59	19	19	189	139	149	10	5	10	292	322	312
29	58	48	38	90	80	80	8	13	13	300	280	250
30	17	27	17	149	119	149	15	15	20	388	308	308
31	21	11	11	159	149	139	5	3	5	215	195	195
32	10	0	2	M	M	M	M	M	M	M	M	M
34	M	M	M	358	338	318	52	37	52	M	M	M
35	20	20	20	88	68	78	18	11	10	1012	872	1012
36	20	10	15	140	120	120	23	28	16	309	329	319
37	0	0	0	150	140	100	12	7	9	317	217	297
38	10	-10	-10	131	121	101	15	9	10	286	266	286
39	-10	-10	-10	M	M	M	M	M	M	M	M	M
41	M	M	M	307	277	287	30	30	30	760	760	750
42	20	10	70	137	97	87	17	15	11	213	213	163
43	0	0	0	145	125	115	6	6	6	194	234	294
44	0	-2	-8	139	139	119	12	15	7	276	306	286
45	M	M	M	56	76	66	8	2	3	211	191	211
46	5	0	-2	M	M	M	M	M	M	M	M	M
48	M	M	M	305	305	295	60	40	40	586	666	656
49	10	10	10	89	72	79	25	5	5	256	266	216
50	-10	-10	-20	121	91	91	10	12	8	278	238	248
51	60	50	50	102	142	82	12	9	9	161	201	191
52	-10	-10	-20	124	104	104	10	8	5	240	270	270
53	40	20	10	M	M	M	M	M	M	M	M	M
55	M	M	M	300	290	310	24	21	21	360	350	550
56	0	0	10	118	98	98	13	18	21	220	240	260
57	20	10	10	93	73	63	9	8	9	320	220	130
58	0	0	40	93	83	43	10	7	12	177	167	247
59	-30	-30	-60	62	62	72	9	8	10	175	215	195

(Continued)

TABLE B-4. (CONCLUDED)

Days of Leaching	Untreated Replicates			Process X Replicates			Process Y Replicates			Process Z Replicates		
	1	2	3	1	2	3	1	2	3	1	2	3
60	-30†	-45	130	N	N	N	N	N	N	N	N	N
62	N	N	N	221*	211	201	29	22	20	400	490	570
63	-10	-10	60	42	42	32	11	11	9	154	144	194
64	10	-80	-30	99	109	69	8	7	7	167	177	167
65	-40	-20	-20	98	88	48	18	7	3	178	128	138
66	-10	40	0	91	91	41	41	0	-16	207	207	117
67	-20	-20	-10	N	N	N	N	N	N	N	N	N
69	N**	N	N	209	219	199	20	26	30	426	356	456
70	0	-10	-10	78	88	58	8	5	1	149	129	139
71	0	-20	-35	77	97	47	16	17	19	222	172	262
72	-10	-10	-10	91	71	51	13	17	16	204	194	214
73	0	-10	0	81	81	51	7	12	14	166	131	226
74	-20	-10	-20	N	N	N	N	N	N	N	N	N
76	N	N	N	250	240	220	-9	-27	-30	440	130	250
77	-10	-20	-10	80	80	40	12	13	12	240	120	180
78	N	N	N	70	80	50	4	4	4	179	159	199
79	-30	-20	-30	80	80	70	9	9	8	190	160	160
80	-20	-20	-20	10	0	10	10	11	9	192	112	182
81	-20	-20	-10	N	N	N	N	N	N	N	N	N
83	N	N	N	240	240	210	22	23	21	347	347	377
84	29	9	-10	80	80	60	8	7	7	166	156	116
85	-3	-23	-18	50	60	60	8	7	6	250	180	220
86	-25	-30	-25	58	58	48	8	7	7	164	154	134
87	-20	-25	-20	N	N	N	7	10	6	158	103	153
88	20	-8	-6	N	N	N	N	N	N	N	N	N
90	N	N	N	110	240	140	21	20	17	570	340	430
91	N	N	N	N	N	N	8	8	8	240	160	190

* All values are in micro-mhos/cm.

** N = not determined.

† Negative conductivity values result from correction for conductivity of blank; they can be ignored.